

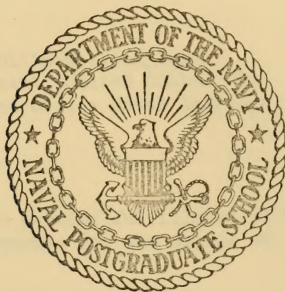
THE DEPENDENCE OF COMPRESSOR FACE DISTORTION  
ON TEST CELL INLET CONFIGURATION

Philip William Tower

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# NAVAL POSTGRADUATE SCHOOL

## Monterey, California



# THESIS

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ON TEST CELL INLET CONFIGURATION

by

Philip William Tower

Thesis Advisor:

Allen E. Fuhs

December 1972

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INLET CONFIGURATION

by

Philip William, Tower  
Lieutenant, United States Navy  
B. S., United States Naval Academy, 1965

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## ABSTRACT

The aircraft turbine engine has evolved to the point that current static test facility designs require modification to provide adequate service and growth potential. Current design procedures are inadequate in that they do not provide methods for the prediction of flow uniformity at the increased thrust and air flow rates now being required.

Through the testing of a multiplicity of inlet models the effect of test cell inlet configuration on engine distortion level is evaluated. A method is developed for the correlation of inlet design characteristics with experimentally observed distortion levels. Together with the evaluation of augmentor performance in an associated thesis by Lt. David L. Bailey, this tentative correlation provides a basis for the development of a practical system for the prediction of the performance of proposed test cell designs.



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## I. INTRODUCTION

The design of sea level test facilities for aircraft gas turbine engines is a demanding and expensive enterprise. Introduction of the turbofan engine configuration and the continuing demand for increased thrust have made the uniformity of the engine inlet air flow a critical design parameter. Techniques are available for the prediction of acoustic, thermal, and, to some extent, atmospheric emission characteristics of proposed test cell designs.

Many industrial concerns whose products are used in test cell construction offer consulting services which can provide pre-construction analysis of these characteristics. Several architectural engineering companies have experience in the design of efficient and durable test cells and can predict many of the details of their operating conditions. One factor which cannot be reliably predicted is the pressure or velocity profile which will exist at the compressor face when a future engine is operated at various power levels in a proposed test facility.

Test cell inlet aerodynamic design can be described as rule-of-thumb. As might be anticipated, this results in occasional, expensive failures, and consistently uneconomical conservatism in design practice. This research was intended to provide a foundation for the application of modern aerodynamics to this current and practical problem.

The air flow through a test cell inlet is of low subsonic velocity and ambient temperature. The lack of a comprehensive, practical method of analysis (such as the USAF DATCOM provides for airframe design) is, therefore, not due to the nature of the aerodynamics involved but rather to the fact that one was not required in the past. Only in recent years





have cases of cell-engine mismatch become relatively frequent occurrences. Test cells designed without concern for the inlet aerodynamics were adequate if sufficiently large. With the generation of aircraft which included the 747 and the C5A, construction of test cells with the required excess of flow capacity became impractical.

Inlet aerodynamics have thus become increasingly critical considerations in facility design, and research became necessary. Many avenues were open for the initiation of this research, and the choice of alternatives received careful consideration.



## II. BACKGROUND

### A. THE CHARACTERISTICS OF FUTURE ENGINES

Sea level engine test facilities designed and constructed in the near future will be expected to provide satisfactory service for twenty years or more. Economically sound test cell design requires the best available information about the characteristics of future engines. Many industrial and governmental planning agencies have direct responsibilities for the maintenance of engine development forecasts. Appendix C, Section II, provides a summary of these forecasts and the information required to obtain timely updates.

These forecasts and Fig. 1 illustrate the changes in engine design which have already resulted in premature obsolescence of many current test facilities. This trend toward increasing thrust, and correspondingly increased air flow rate, which is evident for all engine types, is in many cases coupled with an increase in exhaust temperature. Higher exhaust temperatures increase the quantity of cooling air required in the test cell and further emphasize the need to provide an aerodynamically designed inlet. Future engines will thus require total air flow rates which cannot be provided at the low flow velocities possible in the past. Increasing velocity in the inlet will emphasize its distortion producing characteristics and require proportionally greater flow length for the damping of generated distortion. Additionally, current engines and those proposed to follow them are less able to tolerate distortion than were similar engines in the past.



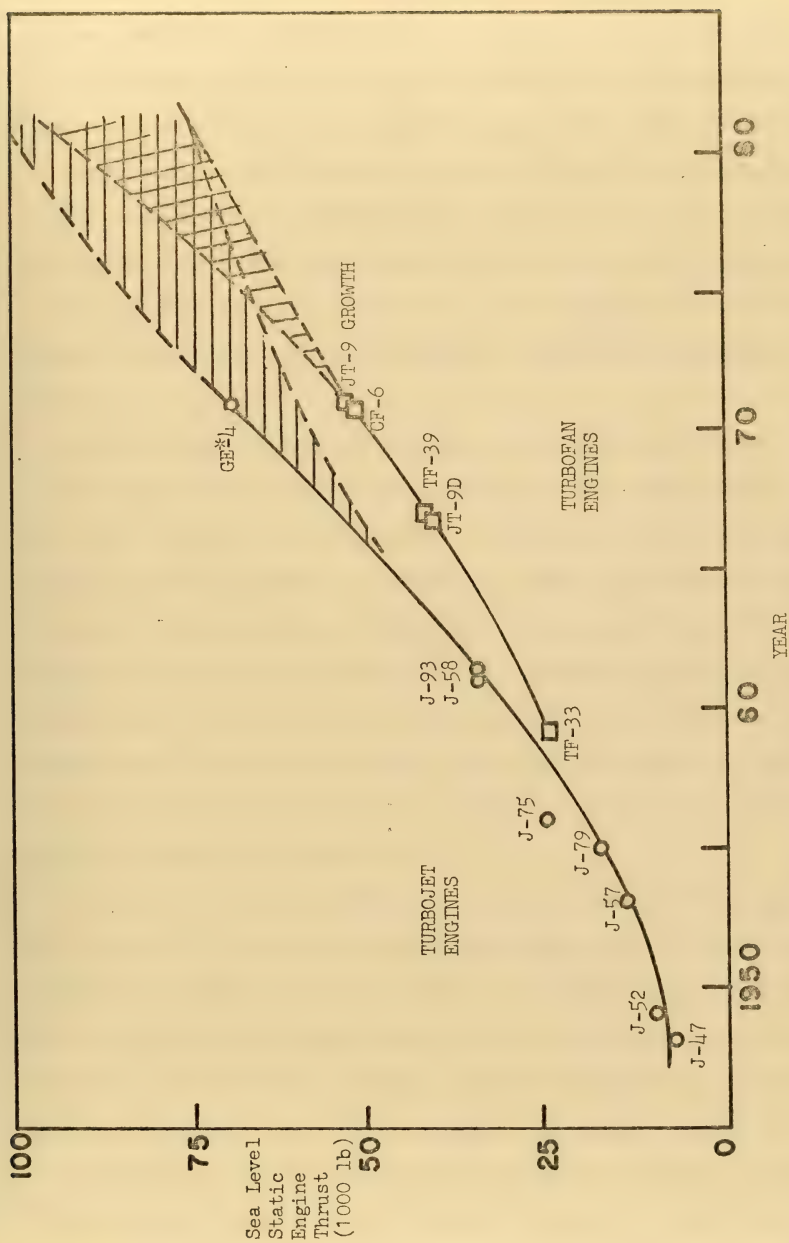


Figure 1. MILITARY AIRCRAFT ENGINE GROWTH



## B. TEST CELL DESIGN REQUIREMENTS

If uniformity of the inlet air flow were the only consideration, test cell design would be a relatively simply matter. Complicating the design process are other considerations each conflicting to some extent with the requirement for uniform flow. Appendix C contains a complete discussion of the factors which must be considered in the evolution of a complete test plant design proposal. Those which most directly influence the inlet design may be classed as structural and environmental [Ref. 17].

Included in the structural category are considerations of real estate costs and availability. Most engines of the turbine type must be tested in the horizontal position. A horizontal cell inlet would contain the fewest sources of distortion. However, this arrangement requires a larger building site than one with an equal length of inlet duct, a portion of which is vertical. The horizontal inlet also adds a requirement for a screened clean area in front of the inlet for protection against foreign object damage. Flow contract devices to improve the inlet aerodynamics must be compatible with the structural requirements for access routes and doors.

A third structural limitation on the inlet layout is the requirement for duct shut off doors to seal the inlet during operation of the fire extinguishing system. This shut off hatch is more simply installed at one side of the ninety degree corner in a vertical inlet configuration than in a horizontal one. Appendix C includes a discussion of the inlet configurations which meet these structural requirements and are in use at current test facilities. Construction techniques and economic considerations also limit the inlet design. An inlet of circular cross





section constructed of polished stainless steel may contribute to good aerodynamic performance; but since experience indicates that less expensive designs can suffice, such a design is impractical.

The other restrictions on the inlet which complicate the analysis and design process are environmental. Nearly all test cell sites require some attenuation of the engine generated acoustic power propagating through the inlet stack. Most of the available means of providing this attenuation involve subdividing the inlet flow, with the attendant multiplication of distortion sources. Acoustic considerations also indicate the use of the vertical inlet stack since this directs the unattenuated sound in the least damaging direction. Proper inlet design must not only account for the effect of the acoustic treatment on inlet uniformity but must provide space and a structurally sound position for their installation. Flow control devices required for the conditioning of the inlet flow will alter the performance of installed acoustic treatment. Close coordination of inlet acoustic and aerodynamic design is necessary for the development of designs satisfactory in both respects.

Environmental considerations also take the form of protection of the test cell from its environment. In addition to screens for FOD (foreign object damage) protection, which through type and placement may contribute to the uniformity of the flow, test cells in some locations have found it advantageous to filter the cell air supply. Removing dust and other atmospheric pollutants improves the service life of cell instrumentation, but filter design and positioning must be considered in light of its effect on flow uniformity as well [Ref. 27].

The exterior environment may also affect the cell operation directly, and inlet design must account for the variation in wind direction,



velocity profile, and humidity [Ref. 3]. Most vertical inlets are covered with rain caps of some type, and some are shielded from prevailing winds. Either may radically change overall inlet aerodynamics [Ref. 4].

Considering the number and variety of factors which must be accounted for in inlet design, it is apparent that the goal of the inlet aerodynamicist must be adequacy rather than perfection. Rather than the development of new and highly refined inlet components, the result of a practical improvement in inlet analysis methods will be a rational method for the arrangement, sizing, and modification of components now being used in test cell construction.

## C. INLET DISTORTION

### 1. Sources

The air entering an aircraft engine during inflight operation is not perfectly uniform. Changes in angle of bank, pitch, and yaw as well as altitude, configuration, and velocity alter the intensity and pattern of this existing distortion. Much effort has gone into the development of aircraft inlets which minimize these effects, but perfect uniformity is not required. As a result, discussion of test cell inlet distortion is confined to consideration of the ways in which the non-uniformity of the flow into the first compressor stage differs in extent and character from that encountered in flight.

The basic properties of the flow through the test cell duct are fixed by the shape and dimensions of the inlet. The most common characteristic of current test facilities is the rectangular cross section of the inlet. Eckert [Ref. 5] provides a summary of current theory of flow of a gas in a rectangular duct. One common conclusion of all investigators



is that sharp corners produce, at all flow rates, extensive distortion effects which persist downstream of the corner for a distance well in excess of that found in test cells.

Cursory examination of typical dimensions for current test cells demonstrates the virtual impossibility of delivering a laminar air stream to the engine (a condition which has been specified in some recent construction proposals, such as Ref. 6). If an inlet cross section of twenty by twenty feet is considered typical, the hydraulic radius (defined as the ratio of duct cross sectional area to duct perimeter) is five feet. An engine requiring just 50 pounds of air per second (typical of the J37 helicopter engine) would produce a velocity of 16.4 feet per second at standard atmospheric density. This results in a duct flow Reynolds number of  $2.06 \times 10^6$  in the open duct and higher values in restricted sections. Considering the natural roughness of typical concrete construction and the natural vorticity of the ambient air supply during windy conditions, it is reasonable to conclude that the transition Reynolds number will be at or near its mean value of 2000.<sup>1</sup> Thus turbulent duct flow is to be expected as well as turbulent boundary layers, on duct surfaces and all flow dividers.

Alternately, the large cross section of the inlet duct might encourage consideration of the flow as equivalent to that over flat plates. At a typical inlet mean velocity of 30 feet per second, a Reynolds number based on length of  $3.5 \times 10^5$  corresponds to a length of

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<sup>1</sup> Eckert and Irvine [Ref. 5] summarize experimental works reporting transition Reynolds numbers varying from 800 to 6000 with duct shape, surface roughness, and vorticity of the ambient air supply.



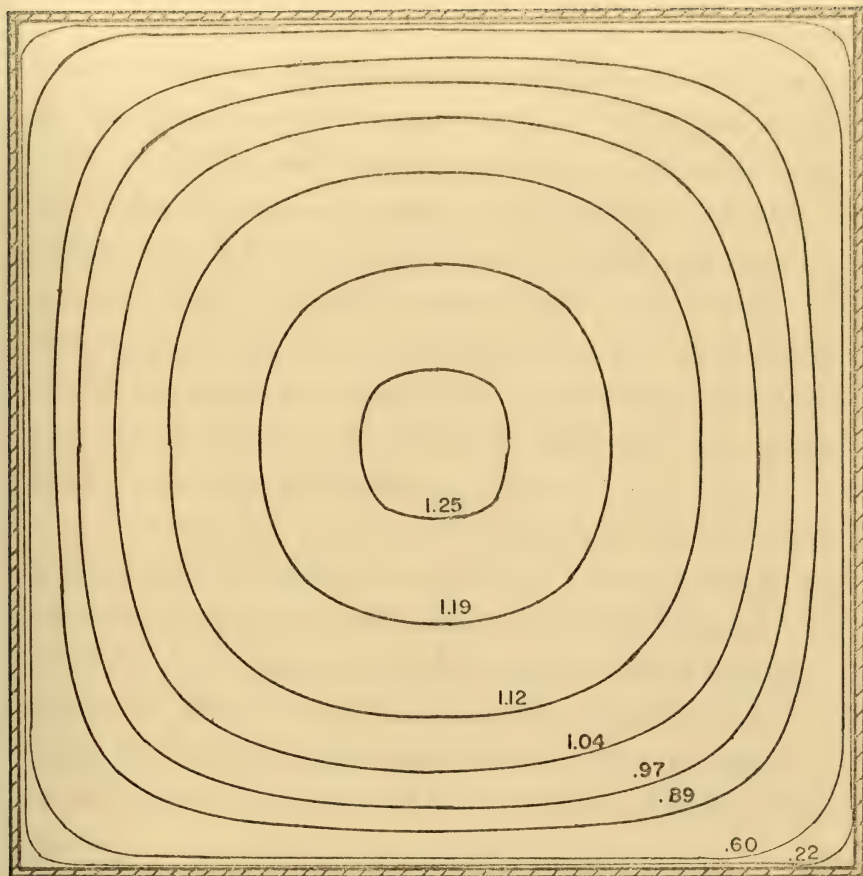
1.10 feet. Although boundary layer transition may be delayed to somewhat higher Reynolds number values by careful conditioning of the flow, the above value is considered typical for a test cell flow [Ref. 7]. Thus a turbulent boundary layer will exist along nearly the entire flow length even if a rough, square leading edge or lip separation produced by external winds do not trip it at the upstream end of the inlet.

Turbulence does not necessarily contribute to the distortion of the compressor flow and can in some cases act to redistribute energy in a manner which smooths out variations in the velocity profile. Both the interaction of the boundary layers in the square corners of the duct [Ref. 8] and the growth on all surfaces immersed in the flow produce momentum deficiency which becomes distortion at the compressor face when the test cell is operated with zero augmentation, i.e. all inlet flow passing through the engine. The extent of this deficiency will be proportional to the total surface area exposed to the flow, and its distribution will depend upon the inlet configuration and position of the engine relative to the inlet components. Coupled with this effect is the development of the velocity profile in the duct flow.

Eckert and Irvine [Ref. 5] report varying estimates of the flow length required to produce a fully developed velocity profile in rectangular ducts. At a minimum, a flow length twenty-five times the hydraulic diameter of the duct has been observed. Current test cells are typically from 8 to 15 hydraulic diameters in length from inlet lip to compressor face. At any power setting then, a developing velocity profile and attendant vorticity are inducted into the engine. Additionally, the development of the velocity profile varies with the mean duct velocity, and distortion so produced will therefore vary with the power setting of an engine under test.







Indicated values are for the ratio  $\frac{V_{\text{local}}}{V_{\text{mean}}}$

Figure 2. THE DISTRIBUTION OF VELOCITY IN A NONCIRCULAR DUCT WITH FULLY DEVELOPED VELOCITY PROFILE.



These considerations apply to flow in an open duct. Most practical inlet designs require acoustic treatment which subdivides the inlet duct into numerous straight or sinuous passages. Within these passages individual velocity profiles develop, and at the trailing edges of the baffles wakes are produced. Acoustic baffles normally have rounded leading edges and streamlined trailing ones to minimize the extent of distortion [Ref. 27], but even the smoothest flat airfoil produces a wake which can persist for considerable distance downstream. To perform their acoustic damping function the surface of most baffles are constructed of perforated sheet metal, an aerodynamically rough surface which enhances boundary layer growth and turbulence generation.

For the typical design shown in Figure 3, the hydraulic radius of the passages between baffles is 0.48 feet. A flow length of 24 feet represents a common average and with this length fully developed flow will occur in these passages. The air discharged from the acoustic baffles will exhibit a highly irregular velocity profile with zero velocity at the baffle surface and, with fifty per cent blockage, a maximum of at least twice the open duct velocity at the center of each passage.

In addition to the acoustic treatment, there are usually other wake generators in the inlet flow duct. These may include structural members for an overhead engine transport system, lights, plumbing for CO<sub>2</sub> injection nozzles, frames for air filters and screens, and observation cameras or windows. If the center line of the inlet duct is not a straight line additional sources of distortion are introduced.

The evolution of secondary velocity components perpendicular to the duct axis is an inevitable result of a change in the direction of a



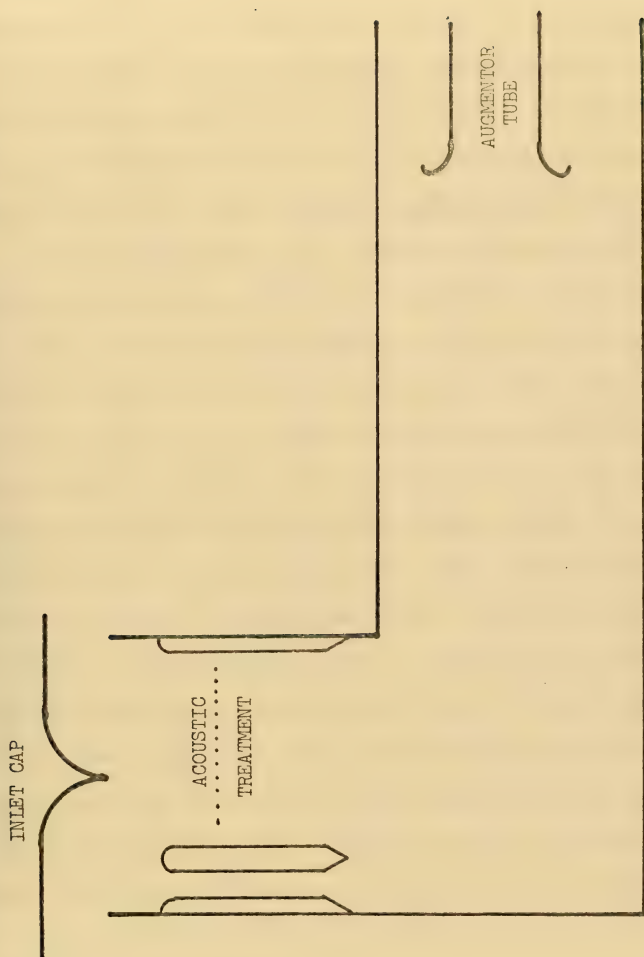


Figure 3. TYPICAL DIVISION OF INLET DUCT BY ACOUSTIC TREATMENT



flowing viscous fluid. Figure 4 illustrates the process of production. Though in some analytical work the effect of this secondary flow is neglected,<sup>1</sup> this can be the case only when the concern is with average flow properties. In the investigation of distortion, the transfer of even one per cent of the flow energy into secondary components will have a significant effect on the detailed shape of the velocity profile. One per cent distortion persisting to the compressor face would use up one half of the stall margin allowed in current engines [Ref. 10].

"In a straight duct with a developing velocity profile the flow possesses axial symmetry. This is no longer true for flow in bends." [Ref. 10]. A velocity profile which is not axially symmetrical at the compressor face is, by definition, distorted. Additionally, while it is common to assume, in the ducted flow of incompressible fluids, that static pressure is constant for a duct cross section perpendicular to the flow, this is not the case for flow around a bend. The construction techniques used in production test cells further complicate the effects of turning the inlet flow since the corner is commonly square at both the minimum and maximum radius. This is, in effect, a variation of the duct area expanding and contracting the flow as it enters and leaves the turn. The sharp corner at the inner radius of the turn can also produce an area of separated flow which causes additional contraction of the flow leaving the turn. The effectiveness of unguided square corners in producing distortion is confirmed in Ref. 10 where a reduction

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<sup>1</sup> "Measurements on a bend of square cross section showed that the energy in the secondary flow after a 90° bend was only about one per cent of the energy associated with the axial velocity distribution " [Ref. 11].





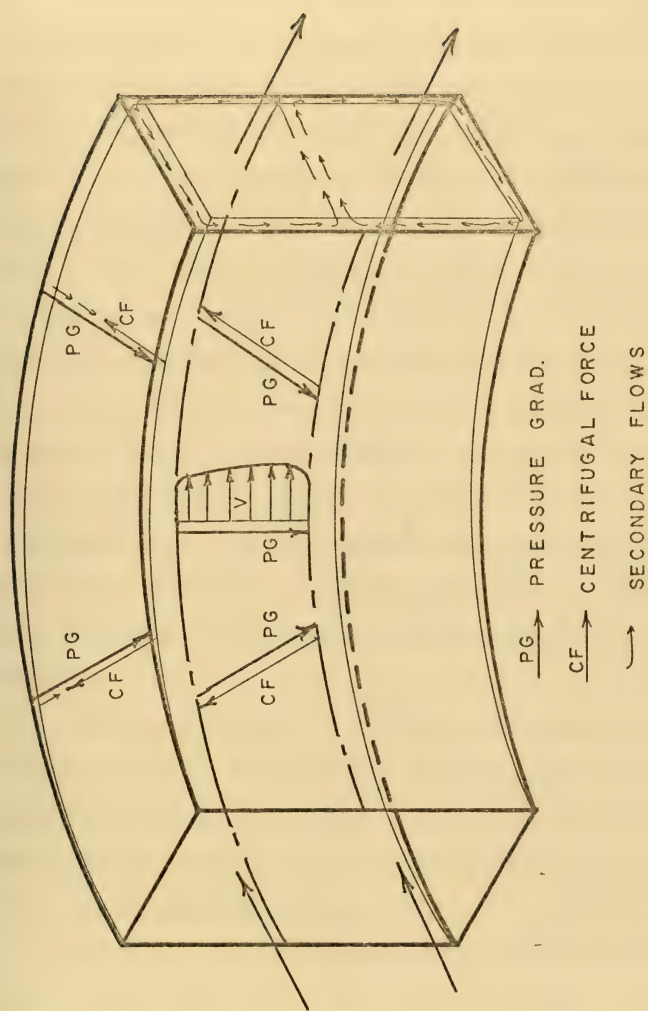


Figure 4. THE GENERATION OF SECONDARY FLOW IN TURNS BY THE IMBALANCE OF CENTRIFUGAL AND PRESSURE GRADIENT FORCES IN THE BOUNDARY LAYER



in distortion from 8 to 2 per cent was observed to result from the installation of turning vanes in the corner.

Augmentation of the engine air supply by routing some of the incoming air past the engine might be expected to reduce distortion by providing an alternate path through the test section for the low velocity flow near the duct walls. Two counter effects leave the final result of increasing augmentation uncertain. The augmentation naturally increases the mean inlet velocity and the consequent probability and extent of flow separation. Also, the addition of a flow past the engine inlet renders the engine susceptible to distortion from another source, the inlet vortex [Ref. 127]. The formation of this vortex, which produces intense localized distortion, is dependent upon many factors including the ratio of inlet and surface velocities and that of inlet diameter to distance from the duct surfaces. An engine undergoing test is at various distances from large plane surfaces and operates in a flow which may contain numerous sources of vorticity. This vortex, normally invisible, may be the source of some otherwise unexplained test cell data discrepancies.

The possible sources of distortion are numerous and to a large extent interrelated. Some variation of the velocity profile will exist in even the best test cell design. The effect of this variation on the engine must be understood before its control is undertaken.

## 2. The Effects of Distortion

The effect of inlet distortion is to cause the blades of the first compressor stage to encounter varying velocities, either along their length (radial distortion) or at various positions during revolution (circumferential distortion). The blade is then at other than



design angle of attack at some position. Compressor blades are designed to tolerate some variation in angle of attack. The stall margin is the expression of this tolerance and represents the maximum variation in angle of attack, lateral extent of the variation, and its position. A distortion of the test cell inlet flow which exceeds the tolerance of the engine is unacceptable and one which is near this limit leaves no margin of safety for occasional transient fluctuations. In the aircraft...

"This distortion may result from the ingestion of hot exhaust gases or low energy boundary layer air from the fuselage or wing surfaces, boundary layer separation within the inlet, inlet lip separation at high angles of yaw or attack, or clear air turbulence " /Ref. 13/

The propagation of these distortions through succeeding stages is highly dependent on the design of the particular engine. Exhaustive testing of a fully instrumented turbofan TF30-P-3 reported in Ref. 13 produced the following picture of distortion history.

A circumferential distortion of 10 per cent<sup>1</sup> was attenuated to less than one per cent at the compressor discharge. Radial distortion of 17 per cent at the compressor face produced no significant distortion of the flow into the combustor but did reduce the absolute pressure level at this position. The circumferential distortion caused a 4.5 per cent loss in fan hub compression efficiency, a 3.6 per cent loss in the core compressor, and a 1.5 per cent decrease in pressure ratio.

"In summary, radial inlet pressure distortion effects on compressor component performance were greatest at the fan and attenuated

---

<sup>1</sup> Defined as the difference between maximum and minimum total pressure divided by the compressor face average.



downstream, whereas, circumferential inlet pressure distortion showed least effect at the fan but an increasing one on downstream components "

/Ref. 13/

Extensive research and developmental engineering effort goes into the determination of distortion sensitivity of every new power plant. References 14 to 20 provide summaries of the work accomplished and underway in the analysis of engine-inlet matching in which distortion is of primary concern. Many of the recent difficulties in the development of the F 111 fighter were the result of excessively distorted velocity profiles being delivered to the compressor. The result of advances in engine technology in the past decade has been the development of engines with greater propulsive efficiency, power, and operating ranges of altitude and speed. One side effect of these improvements has been the reduction of the stall margin in many engines. This condition is responsible for increased research in aircraft inlet design and has two important consequences for the test cell designer and operator. The first of these, as outlined in Section II, is an increase in total cell air requirements, with the overall effect of intensifying the distortion produced in current test facilities. The second is reduction of the permissible distortion level. The total effect then of nonuniformity of the inlet flow is to alter the engine operating condition and the results of static tests. In the extreme case, stall occurs, and the engine cannot be tested safely. In any case, distortion reduces the validity and utility to test results. Inlet design must then reduce distortion to the lowest level consistent with economic, acoustic, and maintenance restrictions.





### III. ANALYSIS METHODS

#### A. REQUIREMENTS

To justify the analysis effort, it must be possible to anticipate a result which will either further the understanding of the natural phenomena involved or be of practical use in the application of existing theory to problems of engineering interest. The nature of the flow through the test cell inlet (low velocity, viscous, ducted, and turbulent) makes it somewhat unlikely that any analysis, however thorough, will contribute substantially to the theory of gas dynamics. The phenomena involved in the production of distortion are, individually, well understood and adequately documented.

It is then a basic requirement that the method of analysis employed be such that its results are amenable to direct engineering application. With regard to test cell design, this implies a flexibility for application to a large number of possible configurations, sizes and flow rates. A complete analysis would involve the accurate prediction of all flow properties at every point in or near the test cell for each possible engine power level and augmentation ratio combination. The ultimate aim of such an analysis system would be the specification of the optimal inlet for any established set of parameter engines, permissible acoustic levels, and land availability. There is, theoretically, no reason why such an analysis system cannot be developed. Some of the possible approaches to the development of such a system are considered in the following paragraphs with a discussion of the probability for success and projected cost of each method.



## B. AVAILABLE ALTERNATIVES

### 1. Direct Integration of the Navier-Stokes Equations

The motion of real fluids and the spatial and temporal variation of flow properties are completely described by the full Navier-Stokes equations. The nature of any Newtonian flow system, including that of air through a test cell inlet, could theoretically be determined by a solution of Navier-Stokes equations. Two characteristics of the inlet flow simplify the form of the equations required to describe this flow. One is the relatively low velocity which permits the assumption of incompressibility to be applied throughout the flow field. The second is the absence of significant heat transfer to or from the inlet flow, which allows its treatment as an adiabatic system.

Given these simplifications and access to a digital computer one might anticipate success in what was once considered an unlikely prospect.

"The theoretical method involves the integration of the equations for unsteady motion in a way which has never been accomplished and which, considering the general intractability of the equations is not promising."

Reynolds (1883)

Several methods for the accomplishment of this unpromising integration are now available [Refs. 21, 22, 23, and 24], and one might consider their application to the prediction of inlet distortion. Two difficulties are quickly evident, and one is the enormously complex nature of the required boundary conditions. Not all inlet surfaces are solid (acoustic treatment usually requires perforated surfaces), and these surfaces are vastly more extensive, numerous, and interactive than any of the combinations found in current literature. Given sufficient talent and resources, it may be possible to overcome this difficulty, but the second peculiarity of this analysis must first be considered.



The duct which comprises the test cell inlet is one of the largest encountered in aeronautical engineering applications. The turbulent nature of the resulting flow does not eliminate the theoretical solution of the Navier-Stokes equations. But, in spite of the computational capacity of the digital computer, it cannot yet approach the almost infinite complexity of nature.

Corrsin [Ref. 23] provides an excellent review of the nature of turbulent flow and the techniques which have been developed for its exact and approximate analysis. The most basic factor in the exact analysis which employs the method of finite differences is the size of the computational grid established within the flow volume. In turbulent flow it is essential that the spacing of these grid points not be greater than the size of the smallest significant motion. The best estimate of the average turbulent eddy size is  $1/10$  the characteristic dimension of the duct [Ref. 23]. If the Reynolds number is greater than  $10^4$  (which it will be in nearly all test cells), the size of the smallest turbulent eddies will be  $10^{-4}$  times the typical test cell characteristic length, or 0.005 feet. "This is the maximum allowable spacing of the lattice points; actually there is significant flow structure which is smaller." [Ref. 21]

Given that adequate numerical methods are available to permit integration of the equations of motion between points, a test cell duct (taking the volume to be the cube of the characteristic dimension) must contain a minimum of  $10^{12}$  lattice points. At each of these, three velocity components and pressure gradients must be evaluated. Even when the cell flow is macroscopically steady, it is decidedly not so on a microscopic scale; hence, temporal variation must also be accounted for.

Additionally, even efficient differencing methods require that fifty to one hundred iterations be made at each point. Computation will then utilize some  $4 \times 10^{14}$  computer storage sites. This is well in excess



of the capacity of even the most advanced current system. It must be clear that while a solution might be attempted by subdivision of the flow system, the effort involved would be enormous, the results short of a complete analysis, and the cost unjustifiable relative even to the cost of a modern jet test facility. No other method is theoretically capable of determining all flow properties at every point so the goal of a full numerical analysis is presently unattainable.

## 2. Simplified Navier-Stokes Equations

If mean flow properties were of sufficient value, the time dependence of the equations of motion might be eliminated and the flow treated as completely steady. Perhaps the greatest simplification would result from the assumption of laminar flow throughout the duct since a large body of theoretical analysis techniques could be used in the analysis. Unfortunately the flow lengths involved in the test cell are so long that the difference between turbulent and laminar boundary layer thicknesses at the downstream end of the inlet approaches the total duct height.

Of perhaps equal assistance would be the assumption of inviscid fluid behavior. Valentine [Ref. 25] provides a complete procedure for the analysis and design of two dimensional ducts for subsonic inviscid fluids. The thickness of the boundary layers which are present in the cell, the wakes of all cross duct obstructions, and viscous damping effects make it unlikely that the results of such an analysis would be useful in distortion prediction. Burggraf [Ref. 23] provides a thorough explanation of the reasons that inviscid analysis cannot account for ducted turning flow phenomena and proposes a form of viscous correction factor. Dwyer [Ref. 22] proposes a method for including viscous effects





in a rapid calculation procedure but points out that the analysis is then restricted to flow upstream of the first separation point. Even in the most carefully designed inlet, areas of separation will occur and cannot be ignored since they will contribute significantly to the distortion level.

The analysis of separated flows has been investigated [Ref. 23], and presumably the established techniques could be combined with a linearized solution of the equations of motion for the flow in the remaining unseparated areas. Again the practical limitations are formidable. Burggraaf [Ref. 23] reports a computation time of 30 minutes for the analysis of the flow past a single circular cylinder at a Reynolds number of 400. He observes that as this number is increased, convergence slows, increasing the number of iterations required, and that the mesh size must be decreased to maintain accuracy. In a qualitative manner, this indicates the effort involved in analyzing a flow at a Reynolds number of the order  $10^6$  passing through the 50 to 100 interacting flow regions of the typical cell inlet.

It thus appears that while theoretically possible, no complete solution of the exact flow equations is practical even when all possible simplifications have been made.

### 3. Approximate Theoretical Methods

A summary of approximate analysis methods applicable to subsonic flow, a portion of which is reproduced in Table I, is presented in Ref. 25. In addition, this reference provides an annotated bibliography with a brief description of the available methods. A review of these makes it apparent that none of these methods can be directly applied to the total cell inlet flow. The following restrictions apply to one or more of these approximate methods:



METHOD	APPLICABLE CONFIGURATIONS	RESULTS
1-D Isentropic gas relations	Symmetric 2-D or axisymmetric shapes with low divergence angles	Inviscid, uniform stream props. and adequate 1st order est. for boundary layer calculations.
Valentine's geometric <u>/Ref. 267</u>	2-D shapes with bends and/or con-divergence	Inviscid flow props. and wall pressure and velocity distribution
Kline and Johnson	Symmetric, non-turning, 2-D 3-D if conical or annular	Pressure recovery for uninstalled diffusers, includes entrance B.L. and corner effects
Shin and Johnston	Curved 2-D diffusers	Performance efficiency as function of turn angle and area ratio
Crosthwait	General shapes	Guidelines for geometrical parameters within which acceptable performance can be expected, based on past test results.
Stanitz	2-D ducts with known wall velocity distributions	Complete inviscid flow field velocity distribution

Table I. SUMMARY OF SUBSONIC FLOW ANALYSIS METHODS



1. One dimensionality
2. Two dimensionality
3. Inviscid flow
4. Uniform flow velocity
5. Straight ducting
6. Fully developed duct flow
7. Purely laminar flow
8. Unseparated flow
9. Circular ducts
10. Potential flows

Any of these restrictions prevent application of the method to the total inlet flow. There remain some general methods dealing with turbulent boundary layer growth and subsonic flow in non-circular ducts. These may be divided into two categories. The first class is based on application of the momentum theorem; and while directly applicable to the inlet, they yield only average flow properties [Refs. 25, 27, 28 and 29]. These are useful in the prediction of test cell depression;<sup>1</sup> however, as detailed in appendix C, this value is usually far less critical than the level of distortion. Since these handbook methods are available for the evaluation of duct pressure losses in the types of components used in test cells, the application of these analytical methods is not justified.

The second class of applicable approximate methods includes those based on turbulent boundary layer theory. Schlichting in Ref. 31 provides as introduction to the theoretical development for these methods and

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<sup>1</sup> Defined as the difference between ambient static pressure and that measured at the engine bellmouth.



additionally provides a comprehensive guide to the available research results. The complex nature of the interior duct surface is again the difficulty in attempting this application. Semi-empirical boundary layer theories are available for the treatment of external flows past flat and curved surfaces and internal flows in unobstructed ducts [Refs. 7, 30, 31, 32, and 33]; however, none of these includes a theoretical development for the region in which the boundary layers of perpendicular surfaces intersect. Additionally, the majority of the empirical data used to determine the values of the exponents in these proposed equations were obtained for areas with fully developed velocity profiles.

Before these boundary layer methods could be applied to the inlet flow, it would be essential to divide the flow into regions which could be treated separately. This division would require prior knowledge of streamline placement and areas of flow separation. The effect of turning, expansion-contraction, screens, and damping lengths could then be individually assessed using available techniques, provided the complete approach velocity profile were available at each component [Refs. 11, 26, 34, 35, 36, and 37]. The validity of this approach would be highly dependent on the division system used. Several methods might be employed to predict the required streamline position data.

#### 4. Electrostatic Modeling

Though it has many inherent limitations, the use of this simulation is so rapid and inexpensive that it must be carefully evaluated. Figure 5 illustrates the type of information available from this method. The most basic limitation is the two-dimensional nature of the technique. The flow is naturally potential; and while streamline spacing may be taken as indicative to 2-D property variation, the effects of turbulence, boundary layer, and circulation are absent.





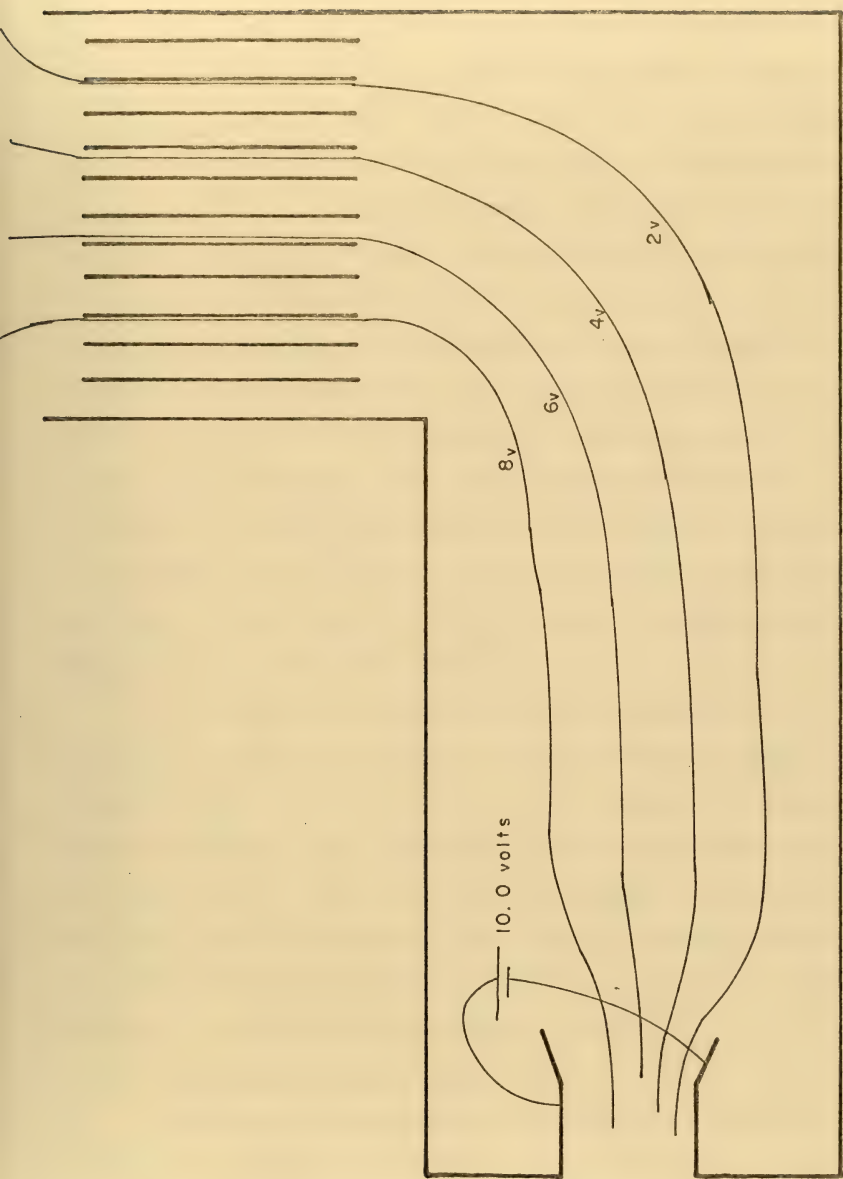


Figure 5. ESTIMATION OF STREAMLINE POSITION BY MEASUREMENT OF ELECTROSTATIC POTENTIALS ON A SLIGHTLY CONDUCTIVE SURFACE



For a first estimate of streamline patterns, this method provides a relatively simple solution with inexpensive equipment and might be used to divide the inlet duct into similar flow regions. Also, a general picture of the effect of component size and position is available through repeated application. By suitable repositioning of the electrode lines and the inclusion of equipotential surfaces in the plot of each duct, it is possible to observe the results of length variation on the uniformity of the velocity profile. With some refinement, namely the inclusion of multiple power sources, the effect of cell augmentation may be included in the study, and an estimate of its effects made. It is possible that the analysis of the inlet flow might be furthered by the comparison of streamline and equipotential surface positions obtained in this manner with those resulting from other theoretical methods. The change of position might be used to evaluate the changes produced by viscosity and vorticity of the flow.

The greatest practical difficulty in this analysis is the necessity to produce an entirely new conductive drawing for each configuration tested. The ability to assemble the layouts from component pieces would simplify the procedure and is considered feasible with some modification of commercially furnished equipment. The classroom instructor kit manufactured by the Pasco Scientific Company was used in the evaluation of this procedure and should provide adequate for initial attempts to continue investigation with this method.

#### 5. Three Dimensional Scale Models

Construction and operation of inlet scale models offers the opportunity to include in the analysis the natural effects of geometry, viscosity, and turbulence which contribute to the character of the



velocity distribution in the actual cell. Model studies by-pass the difficulties of the theoretical mathematical treatment, but in doing so create other difficulties. Without a theoretical basis to predict the results, the analyst must develop a system which permits the test results to be generalized. In specific cases, where a single proposed design is of interest, an instrumented model is the most efficient means of analysis currently available. Even in this single configuration case, careful consideration must be given to the selection of instrumentation, scaling factors, and the simulation of power settings and augmentation ratios. Reference 38 is typical of the results that can be obtained through this type of analysis. Many of the considerations necessary for this effort are similar to those involved in wind tunnel operation. The numerous references available in this field and the utilization of personnel experienced in tunnel design and operation can be expected to simplify this form of inlet analysis and increase confidence in the results.

While an analysis of model inlet test data cannot be expected to meet the goal of full understanding of all flow properties, it can meet the analysis requirement of permitting direct engineering application. Properly conducted, this analysis also can approach the goal of inlet design optimization. The following section considers the questions which must be resolved in the design of an inlet model test program before results can be applied to inlet configurations in general.



#### IV. INLET MODEL TESTS

##### A. GENERAL CONSIDERATIONS

Perhaps the most general concern in model studies is that of economy. This takes many forms, and one of these is generality of the results. The models must be designed, constructed, and operated in such a way that the results permit valid conclusions to be reached concerning full scale systems. The fewer the restrictions on the application of the results to a wide variety of possible configurations, the greater the economy of the operation.

It is necessary to test a multiplicity of configurations to achieve any degree of generality. Minimization of cost and effort in the construction of necessary number of models will be furthered by the utilization of interchangeable modular components. Economy also is necessary in the handling of the experimental data. Even with minimum instrumentation, the requirement for tests of numerous configurations and operating conditions can be expected to produce a large quantity of data. Processing methods must be planned to efficiently handle this data while providing the flexibility required for the establishment of correlation and prediction methods.

##### B. CONSTRUCTION

###### 1. Selection Criteria

Prior to the design of the model several decisions were necessary concerning: scale, materials, configuration, and assembly methods. Single piece models have been constructed for use in test programs conducted to evaluate the performance of specific proposed inlet designs





[Ref. 38]7. Interchangeable model components reduce greatly the cost of providing the required number of different inlet configurations.

The ability to repeatedly assemble the model components required the utilization of a construction material other than the cast concrete used in actual cell construction. Sheet metal was a logical alternative since it is low in cost, and assembly was possible in the available laboratory work shops. The models constructed for the tests reported in Ref. 38 were constructed in this manner. The pressure loss of the inlet flow results in an inward force on the model walls which will deform the duct cross section if the construction material lacks sufficient stiffness. With sheetmetal this requires a wall thickness which could result in a total model weight in excess of that which would be encountered if a concrete model were built. The metal models referred to above utilized exterior stiffeners to meet the deformation requirements and avoid excessive weight. Addition of this bracing to the components of a modular design would greatly complicate the design of the required subassemblies.

This design was simplified by the use of lighter, stiffer material. In selecting this material it was recognized that since model tests are empirical in nature, circumspection required that no prior assumptions be made as to the type of test information which would be significant. The metal models used included glass viewing windows which permitted both still and motion picture records to be made of the motion of flow visualization tufts. Construction of the entire model from transparent material was a logical extension of this technique. The use of glass would have required refined assembly techniques not readily available, though this material would be suitable in other respects. The acrylic resin material, commercial Plexiglas, was also considered. In addition



to transparency, Plexiglas is relatively low in cost and can be machined by experienced model makers. Its stiffness makes external bracing unnecessary for most span widths, and it is tougher than glass which was of considerable importance in lengthy test programs where extensive handling would be required. Construction experience sufficient to meet the requirements for accuracy of dimension and alignment was available at the Naval Postgraduate School model shop, and Plexiglas was, therefore, selected as the primary construction material for the present investigation.

In the selection of required model configurations, a brief examination of the available specifications for current test cells made it clear that even an ambitious test program could not include all possible designs. Since no claim of optimality had been advanced for any current design, a truly complete test program would have to include every practical configuration not yet utilized. The model construction had to include as many of the major variations in inlet design as possible. However construction of more configurations than could be tested during the proposed program duration was avoided. The limited number of components constructed for this investigation were sufficient to assemble 718 inlet configurations of practical significance. Multiplying these by the number of power levels and augmentation ratios which were selectable, more than sufficient combinations were available for investigation.

Most critical to the acquisition of valid test results was the choice of model scale factor. Practical considerations limited this choice, since a large model is difficult to reassemble frequently and requires a power source approaching the capacity of the jet engines



tested in the actual test cells. Large models also increase material costs, and the increased span of the walls makes the requirement for external stiffeners more probable, depending upon the material and the wall thickness. On the opposite end of the scale, size limits are imposed by the extent of the necessary instrumentation because miniaturization rapidly increases both cost and complexity. As the scale factor increases, there is also increased fineness of detail required along with precision of construction methods.

For construction from Plexiglas the duct cross section was considered to be limited between 6 x 6 inches and 3 x 3 feet. Besides those effects mentioned above, variation of the model scale results in alteration of the Reynolds number of the inlet flow. Since this dimensionless flow parameter is a function of both flow velocity and duct size, it can be held constant only if flow velocity is increased inversely to the reduction in duct dimensions. Thus a model using air as the fluid and having a 12 x 12 inch duct cross section would require a flow velocity 24 times that occurring in a 24 foot square test cell. Exact Reynolds number similarity between model and cell could be expected to eliminate one source of possible test discrepancies. Many experiments in gas dynamics have been conducted to determine the importance of this similarity in flows over a wide range of Reynolds numbers.

In the case of the test cell model this requirement for flow Reynolds numbers equal to those of the full scale cell would reduce rather than increase the validity of the test results. In the test cell, flow velocities are normally limited to a maximum of 50 feet per second in the open duct. This low subsonic velocity (Mach number less than 0.05) is the primary characteristic of the flow and the type of components



which can affect the distortion level. If the model were to be operated at an equal Reynolds number, the Mach number of the model flow would be 0.96. In the portions of the duct where flow area are reduced, this would cause supersonic flow, and even in the open duct, compressibility effects would alter the nature of the flow.

It is then necessary that the flow in the model, if it is of the same fluid and occurs in the same Mach number regime, be at a different Reynolds number. Although exact similarity is not possible, it is necessary that the nature of the boundary layer and wakes formed in the model be the same as those found in the cell. In this regard, Kays [Ref. 17] provides a complete summary of the flow regimes for air. For a sea-level test facility with a 24 foot square cross section and a mean flow velocity of 35 feet per second, the Reynolds number based on hydraulic diameter is  $5.32 \times 10^6$ . For a one twentyfourth scale model of this cell operated at 20 feet per second, this number is  $1.27 \times 10^5$ . Schlichting [Ref. 31] demonstrates that the duct flow type which includes the flow in the actual cell extends down to at least  $10^4$  and under conditions of initial flow vorticity, to  $5 \times 10^3$ . Thus, while this scale factor does not permit Reynolds number equality to be maintained at this velocity, it does produce a flow which has the same character and is subject to the same major distorting effects. Sherman [Ref. 39] provides experimental confirmation of Reynolds number independence.

These decisions, made individually to meet the existing selection criteria for model testing, collectively establish the model design requirements. The resulting design for the one twentyfourth scale model components is detailed in the following section.





## 2. Component Descriptions

The horizontal portion of the inlet duct included test sections and a horizontal flow straightening section which were used in all tested configurations. Upstream of these was the convertible turning section which made the inlet either a horizontal or vertical one. The test section housed the instrumented engine model and static depression ports for the measurement of cell depression. With the turning section assembled for vertical flow, either a straight vertical stack or a double bend, back and up, section could be placed on top of it. Three inlet caps could be placed on top of the vertical stack, and three types of acoustic treatment models were available. These treatments were designed to permit their installation in the horizontal flow straightening section, the vertical stack, or between the second and first turns of the triple bend configuration.

A turning vane model was available which could support seven equally spaced vanes or any combination of lesser numbers. This assembly could be placed either in the single turn of the vertical inlet configurations or in the second or third turn of the S curve inlet. The hex section flow straightening assembly permitted its use in any of the horizontal or vertical duct sections. Figures 6 through 21 provide photographic views of these components and dimensioned sketches of each, together with views of typical assembled configurations. Except where otherwise noted, the construction material was Plexiglas 0.25 inches thick.



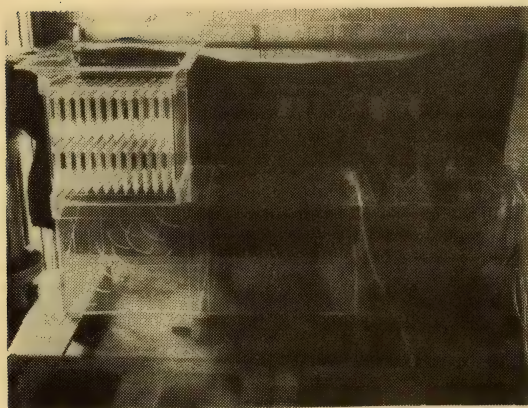
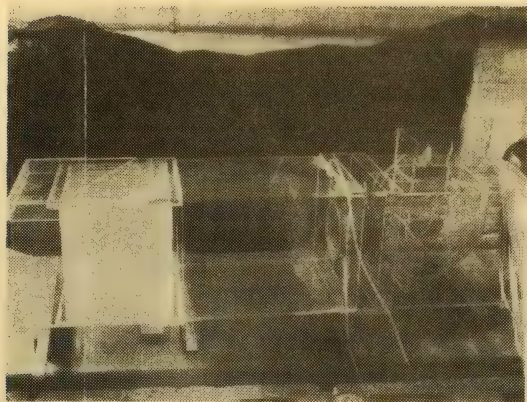


Figure 6. ASSEMBLED MODELS, NON-AUGMENTED FLOW



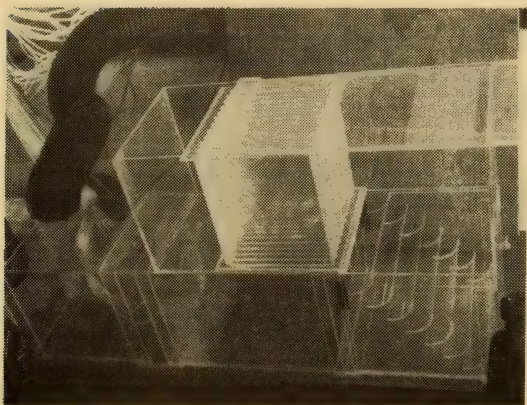
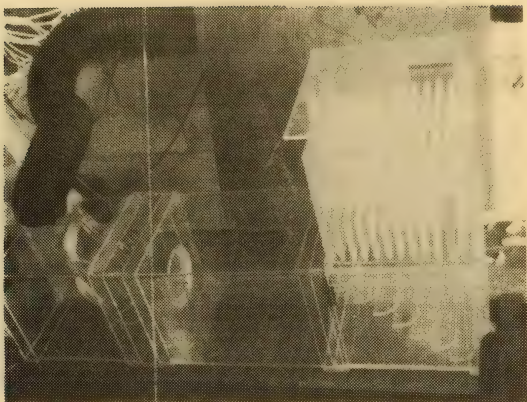


Figure 7. ASSEMBLED MODELS, AUGMENTED FLOW





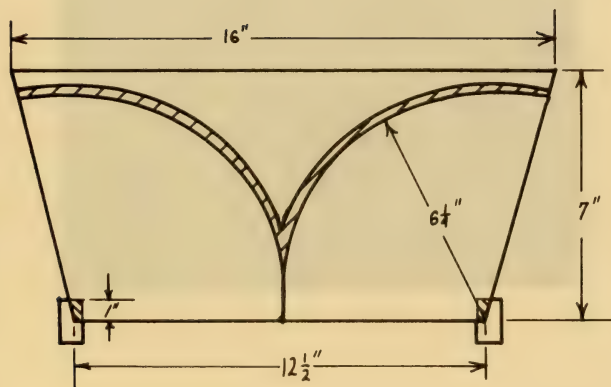
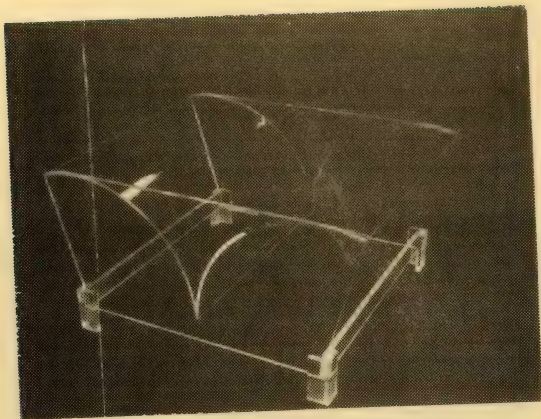


Figure 8. BI-DIRECTIONAL INLET CAP





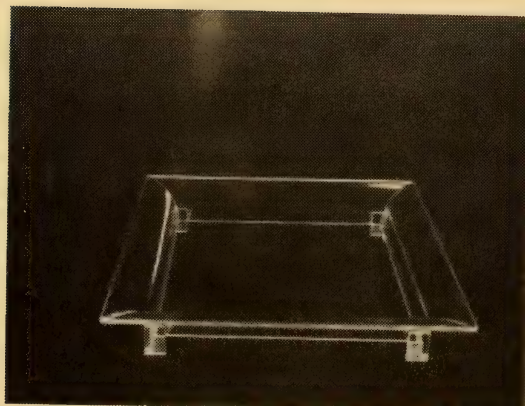
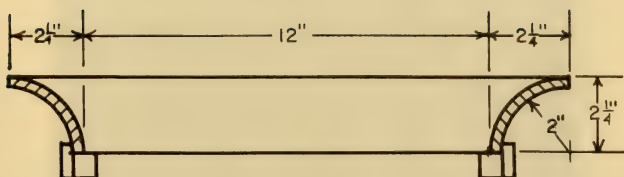


Figure 9. FAIRED INLET CAP



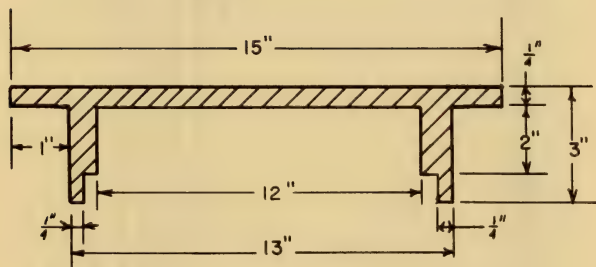
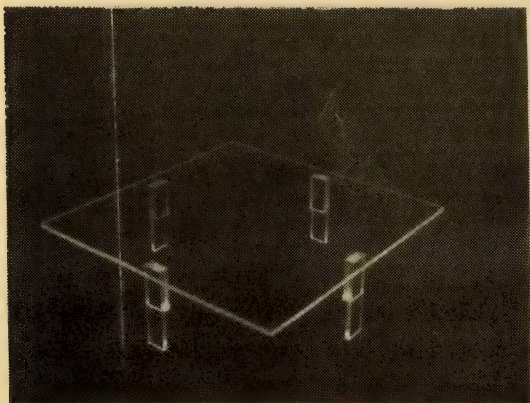


Figure 10. FLAT PLATE INLET CAP



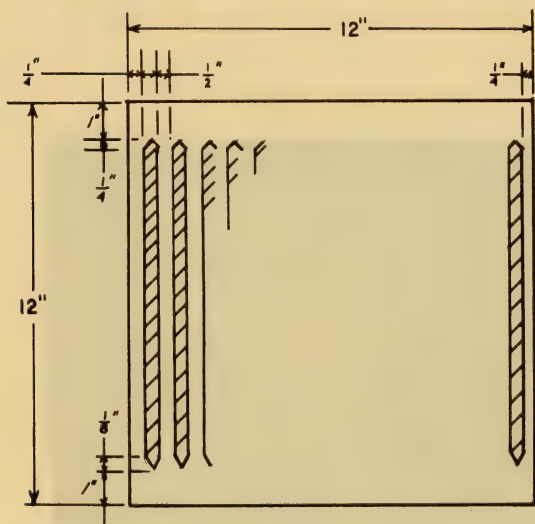
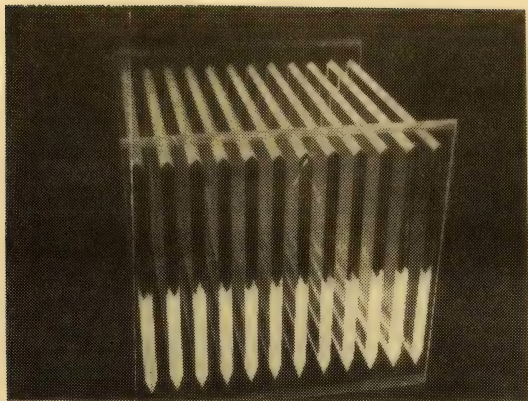


Figure 11. FLAT BAFFLE ACOUSTIC TREATMENT



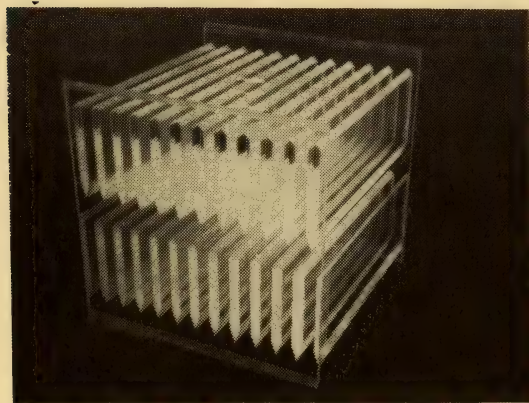
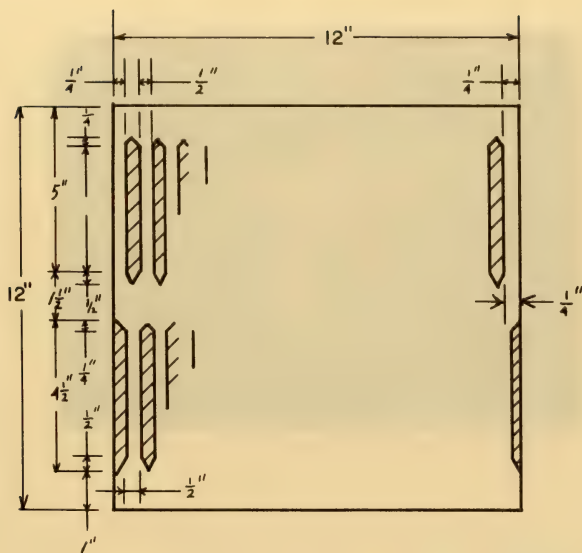


Figure 12. STAGGERED BAFFLE ACOUSTIC TREATMENT





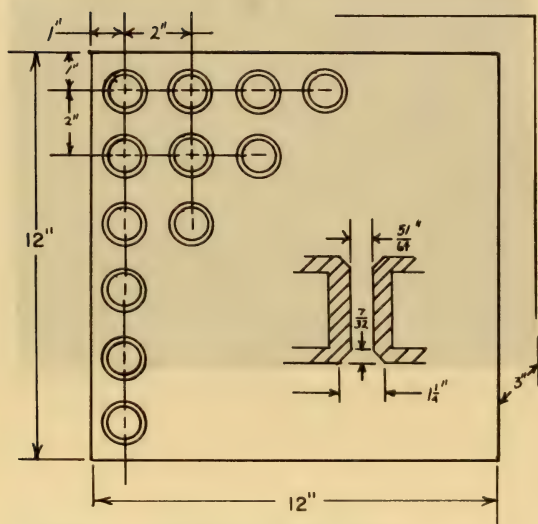
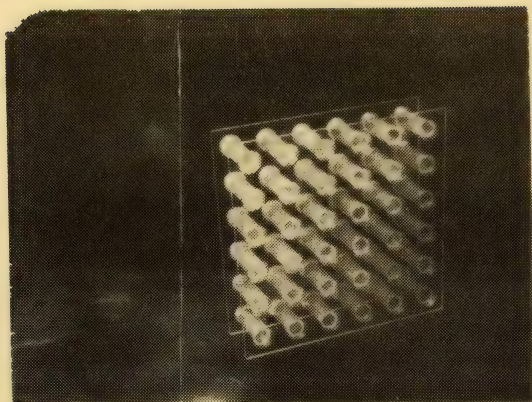


Figure 13. TUBULAR ACOUSTIC TREATMENT



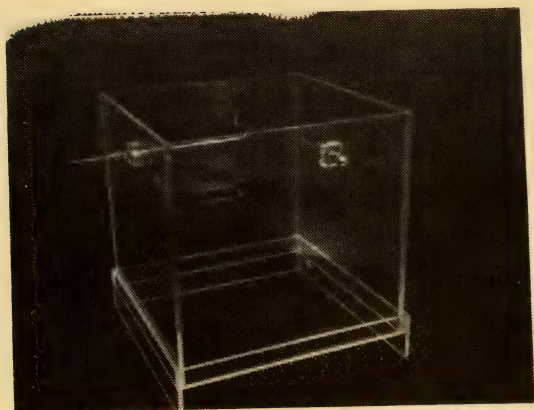
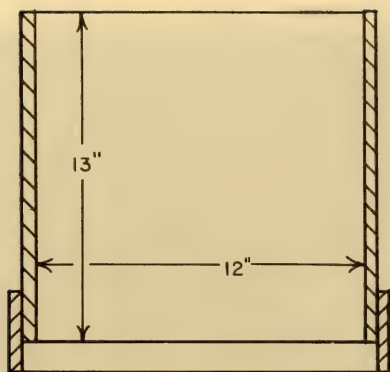


Figure 14. VERTICAL INLET STACK



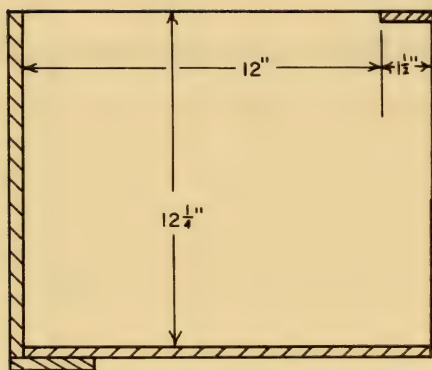
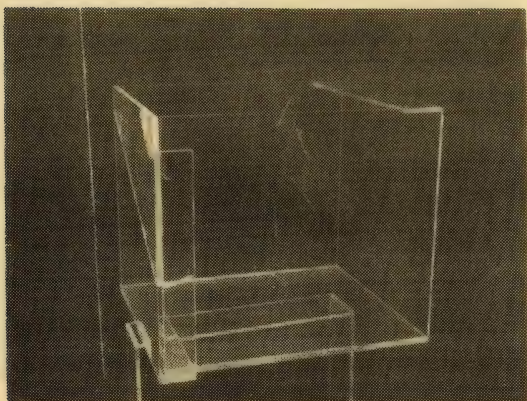


Figure 15. CONVERTIBLE DUCT BEND



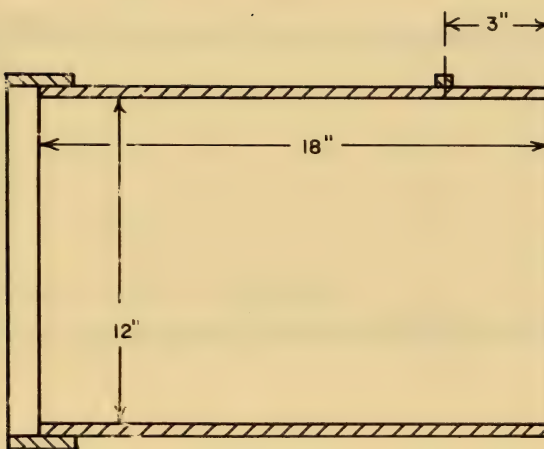
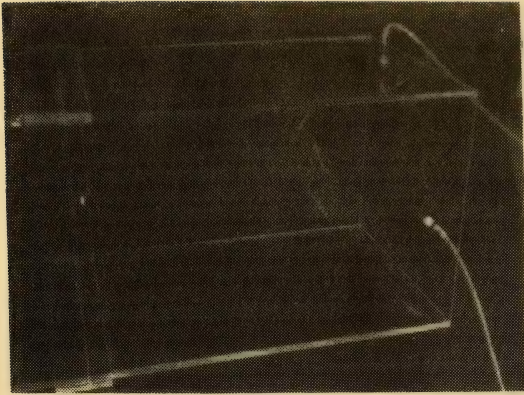


Figure 16. FLOW STRAIGHTENER COMPONENT





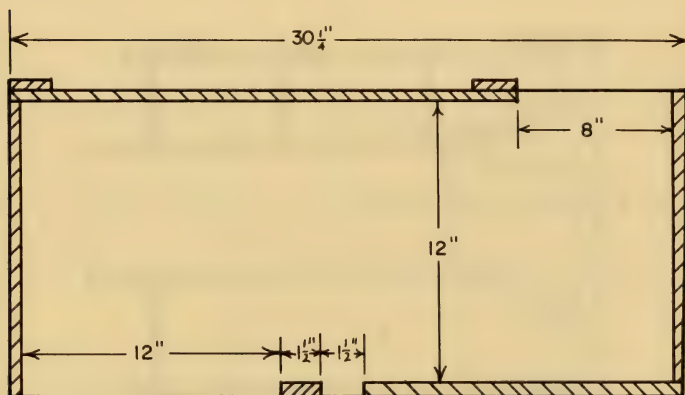
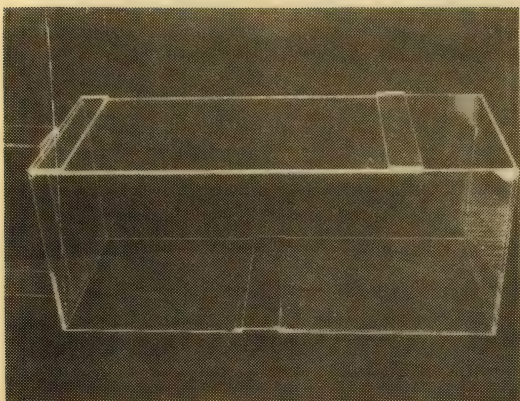


Figure 17. TRIPLE TURN INLET BOX COMPONENT



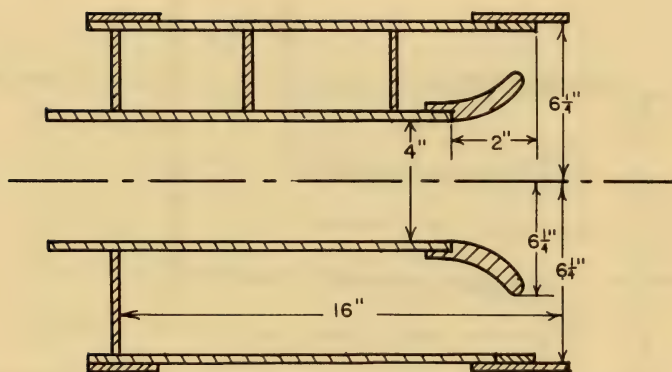
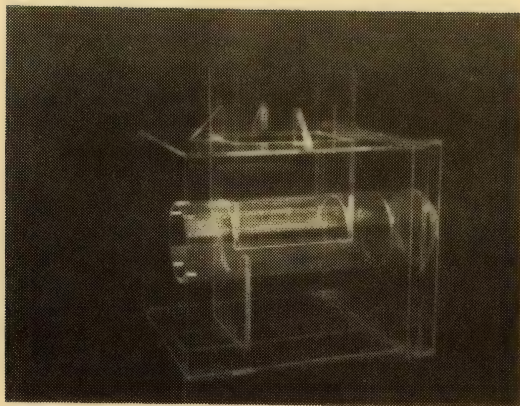


Figure 18. ZERO AUGMENTATION TEST SECTION



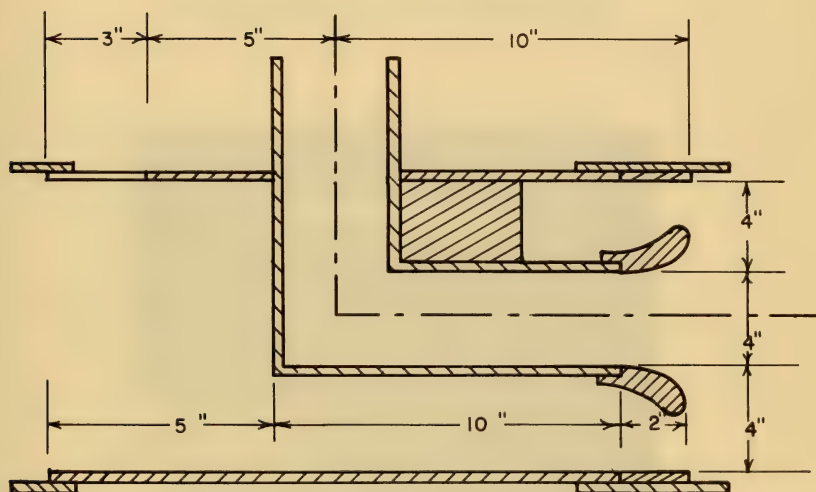
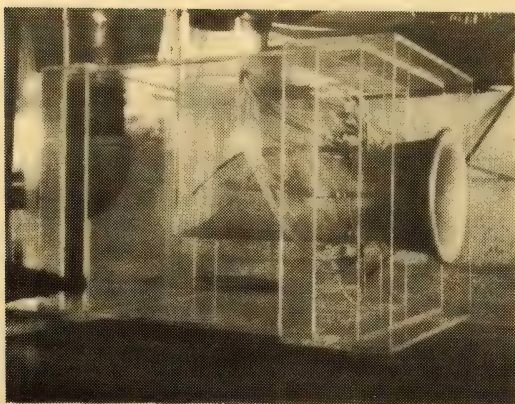


Figure 19. DUAL POWER TEST SECTION





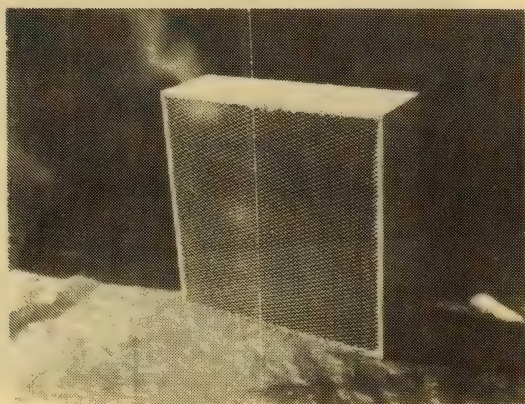
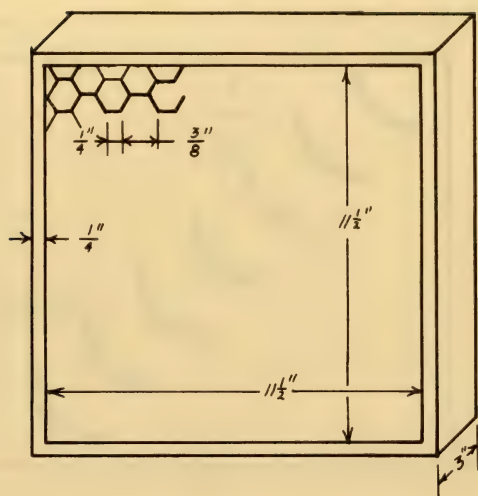


Figure 20. HEX SECTION FLOW STRAIGHTENER





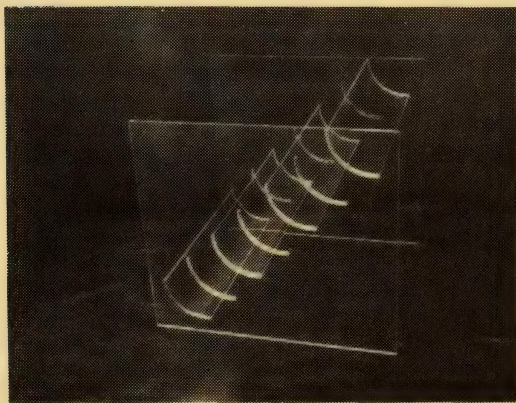
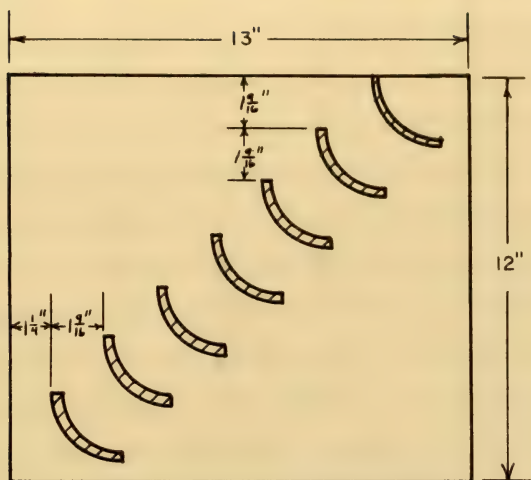


Figure 21. TURNING VANE ASSEMBLY



## C. POWER SUPPLY SELECTION

### 1. Requirements

The critical requirement for the model power supply is that it be of a size appropriate to the scale of the model. Flow in both the test cell and the model will be turbulent even at very low velocities.<sup>1</sup> This is due to the relatively large cross section of the duct compared to that of a typical turbulent eddy. Also, as detailed in previous sections, the flow through the test cell will not approach full velocity profile development. Typically, cell flow lengths vary from 3 to 6 times the hydraulic diameter of the open duct. It was thus considered reasonable to scale the length of the model in a similar manner. This has the effect of producing a flow which occupies the same fraction of the duct entrance length and permits the same analysis methods to be applied to both situations. The selection of the model power source must be based on the flow velocity required in the model for maximum similarity of distortion.

Distortion of the engine air supply results from the existence of regions of momentum deficiency. Boundary layer theory includes the definition of a momentum thickness which is developed as a specific measure of this deficiency [Refs. 7 and 31]. At any duct cross section the percentage of the flow which has lost momentum due to surface friction is equal to the percentage of the duct area within the momentum thickness of the boundary layers. If the test cell and model consisted of sharp lip, straight, open ducts, the percentage distortion existing

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<sup>1</sup>Reference 6 includes a design requirement that laminar flow be delivered to the engine. In a 24 foot duct with a 100 foot flow length, delivery of laminar flow could be accomplished at a maximum velocity of 0.003 feet per second if the transition Reynolds number is taken as 2000.



at any position, including the critical compressor face, would be exactly equal if the ratio of momentum boundary layer area to duct area was the same in the two ducts. Test cells and their models are not ducts with this simplicity of arrangement and contain many secondary surfaces which also form boundary layers and produce pressure gradients affecting layer growth in their vicinity. Still maintenance of this area ratio at equal values in cell and model will insure that one major source of distortion will be available for measurement in the laboratory.

Figure 22 is a schematic representation of open duct flow where  $D$  is the momentum thickness of the boundary layer. For a square duct with side length of  $L$  feet and total area  $L^2$ , the area of the Momentum Boundary Layer (MBLA) is

$$MBLA = L^2 - (L - 2D)^2$$

The distortion percentage or distortion area ratio is

$$\frac{MBLA}{A} = \frac{L^2 - (L - 2D)^2}{L^2} = \frac{4D}{L} - \frac{4D^2}{L^2}$$

The condition for similarity of distortion in cell and model is that this ratio be equal in each case or

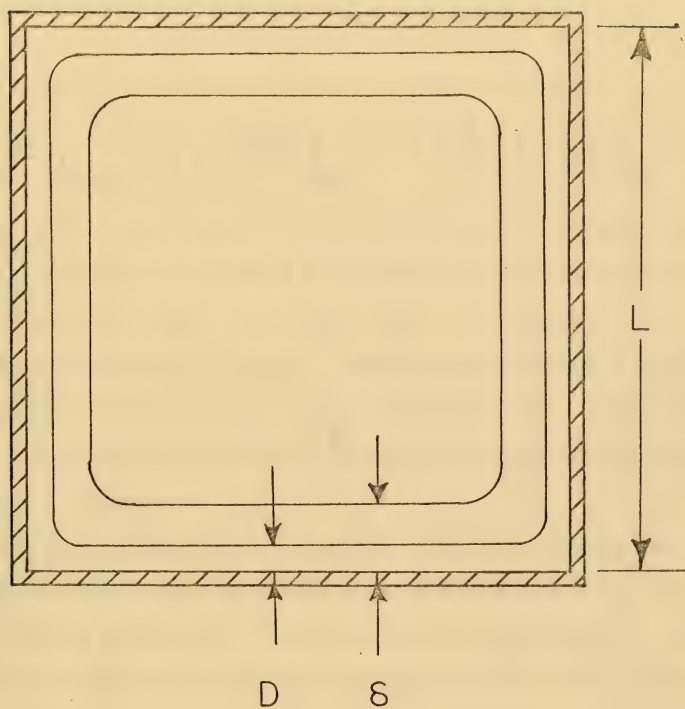
$$\left( \frac{D}{L} - \frac{D^2}{L^2} \right)_{\text{MODEL}} = \left( \frac{D}{L} - \frac{D^2}{L^2} \right)_{\text{CELL}}$$

The thickness of this momentum boundary layer is a function of flow velocity and length, assuming that surface roughness is held approximately constant. Kays [Ref. 7] reports this expression as the best approximation of this thickness:

$$\frac{D}{x} = 0.037 \left( \frac{\nu}{Vx} \right)^{0.2}$$

where  $x$  is the flow length,  $V$  is the duct center line velocity, and





$D$  - Boundary Layer Momentum Thickness

$\delta$  - Boundary Layer Thickness

$L$  - Duct Height

Figure 22. SCHEMATIC DUCT FLOW CROSS SECTION





$\nu$  is the kinematic viscosity coefficient. At sea level  $\nu = 1.5757 \times 10^{-4}$  ft<sup>2</sup>/sec. Thus taking

$$B \equiv 0.037 \nu^{0.2} = 0.1741$$

the displacement thickness is:

$$D = B V^{-.2} X^{0.8}$$

The requirement for similarity of flow may thus be written as

$$B \left( \frac{V^{-.2} X^{.8}}{L} \right)_{MODEL} - B^2 \left( \frac{V^{-.4} X^{1.6}}{L^2} \right)_{MODEL} = B \left( \frac{V^{-.2} X^{.8}}{L} \right)_{CELL} - B^2 \left( \frac{V^{-.4} X^{1.6}}{L^2} \right)_{CELL}$$

Fixing  $V_{cell}$  at a common value of 40 feet per second, and having fixed  $L_{model} : L_{cell}$  at 1.24, examination of the above relation revealed that the selection of the power which sets the model flow velocity, also fixes the length ratio  $x_{model}/x_{cell}$ . The selected power source was required to produce a realistic value for this length ratio. Figure 23 presents the results of the complete analysis and the full development is included as Appendix A.

The selected power source also had to meet requirements for flexibility. Engines operate in test cells at idle power and at max thrust including afterburner. The air flow in the inlet duct is a function of engine power and also of cell augmentation ratio, AR, defined as the ratio of mass flow rate past the engine to the flow rate through it. Commonly, this ratio varies from zero (close coupled exhaust) to three (in facilities treating the exhaust gases for introduction into pollution control devices). The above analysis utilized the open duct velocity as the independent variable and must be somewhat extended to assess the effect of power variation.



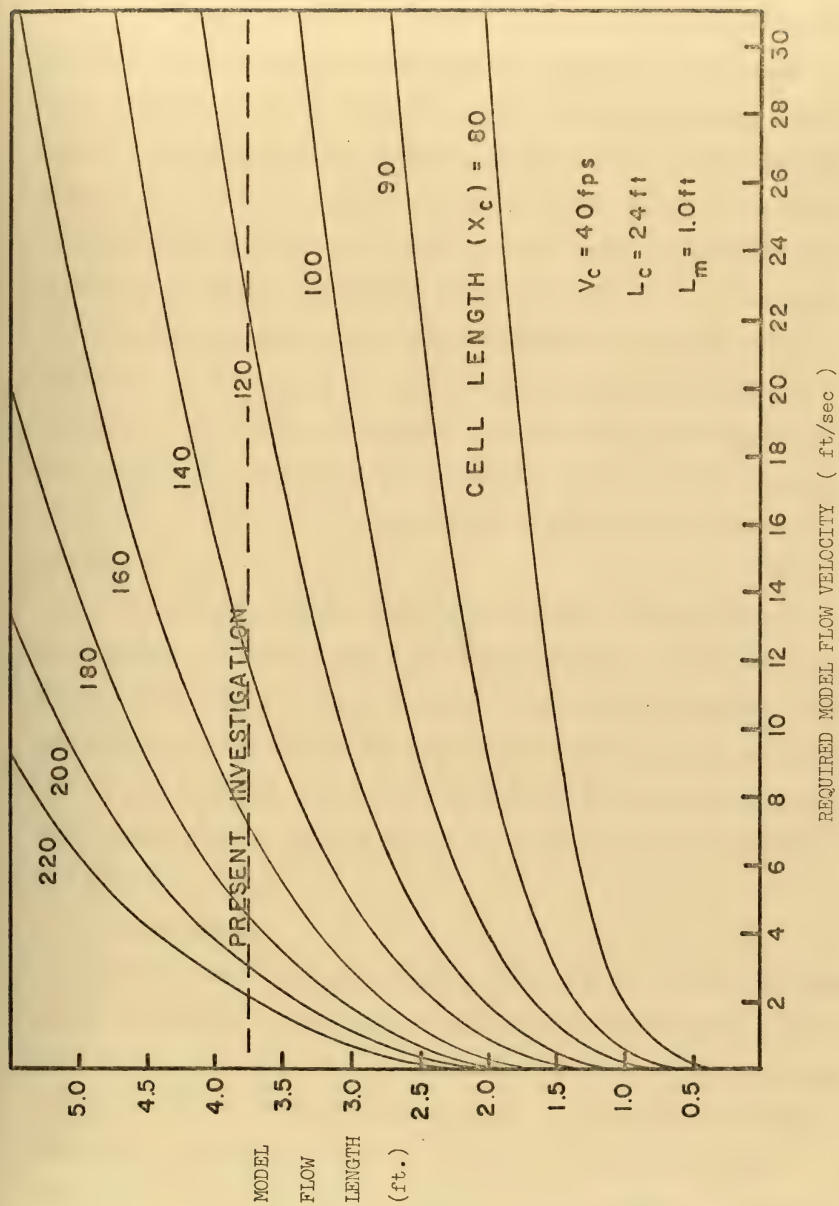


Figure 23. VARIATION OF LENGTH SCALE FACTOR WITH MODEL VELOCITY



The model length ratio is fixed utilizing maximum predicted air flow for the test cell and the corresponding maximum flow velocity. Then, referring to the previous form of the similarity expression, the length ratio is observed to be fixed. In this case, the effect of model velocity variation is to change the velocity scale factor of the test in accordance with Figure 23. The power source must therefore be capable of varying the model flow velocity in increments the size of which are available from the desired cell velocity variation increment size and Figure 23. In the case of the tests conducted during the present investigation, the change in compressor face distortion resulting from a one foot per second variation in velocity was desired. This implies a requirement that the power source be able to provide a sensitivity of 0.6 fps.

This is the limiting sensitivity criterion for the suction power source. Figure 23 shows that a source with low capacity can simulate only extremely long test cells. Practical considerations also limited this selection since the power unit would be required to operate for extended test periods and for a total usage in excess of 300 hours. Total program economy was best served by considering inherent durability as a selection factor.

## 2. Alternatives

Four primary power sources were considered for use with the inlet model. Reference 38 is a report on model tests conducted using a scale model turbine engine operated by compressed nitrogen. Both hot and cold gas models have been used in the development of methods for simulating engine power effects in wind tunnel testing. In nearly every case satisfactory simulation required complex, sensitive models. The cost



of most model engines with the capacity to operate a cell inlet model was high enough to make their use impractical except for an organization which has them internally available. Model studies conducted for the investigation of other cell flow phenomena may require the use of scaled engine models; but for the purpose of inlet studies, simpler and less expensive power methods are available.

A vacuum or high pressure source may be used to induce the require flow in the model. Suction, when applied to an appropriately scaled model bellmouth, has the advantage of natural similarity with test cell flow. The application of high pressure air to the inlet would have involved considerable difficulty in the simulation of the natural environment of a test cell. Simulation of the turbulence level of the atmosphere would have required extensive treatment of the power supply outlet flow by screening and/or contraction-expansion sections [Ref. 40]. To permit natural streamline patterns around the cell model, it would have been necessary to submerge the inlet deeply within a pressure supply plenum to prevent interference effects from the plenum walls.

A suction powered model avoids these complications by permitting the model to use air from ambient room conditions and simplifies the simulation of external wind conditions if desired.<sup>1</sup> The suction power supply could have been either a type of vacuum pump or the intake of a rotating blower. The choice in this case was a function of availability and model scale. Most vacuum pumps of reasonable cost have flow capacities which limit their use to models of the smallest size unless a

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<sup>1</sup> Leef [Ref. 47] reports the dependence of distortion on external wind direction and velocity and examines in depth some methods of its reduction.





sizeable holding tank system is employed and testing is scheduled to meet the required recharge time. The rotating blower is available in sizes to meet much larger model flow requirements. They are typically low in maintenance cost and provide unlimited test run time in most cases. With either the pump or blower it is necessary to provide ducting which permits the flow to be divided between primary (engine) and secondary (augmentation) flows. High pressure supply systems would have to be confined to the testing of zero augmentation configurations since no provision for this division is readily available.

Another method of providing power to the model was to use a simplified engine model in the form of an injector nozzle supplied from a high pressure source using the nozzle discharge to induce both primary and secondary flows. The quantity of flow required of the supply source imposes an additional limit on model size by the dimensions of the supply piping required. The greatest difficulty anticipated in the use of this arrangement was the provision of adequately sensitive control of the two flow rates.

### 3. The Selected Power System

This investigation was conducted in conjunction with the research reported in Ref. 41. As that investigation of test cell augmentor flow required accurate simulation of the engine exhaust, a pressure fed ejector nozzle was constructed. To overcome the difficulty of providing control of the flow rate and permit a more uniform exhaust flow, an additional power source was used to provide engine flow. A rotary cage blower with a flow capacity of 0.7 pounds per second was separately ducted to the model engine bellmouth. Thus in the dual power mode, the air passing through the compressor face was exhausted through the blower



discharge and the augmentation air together with the nozzle supply flow exited through one of a variety of instrumented augmentor ducts.

At an augmentation ratio of 3.0 a total inlet flow of 1.94 pounds per second was measured in the model. In this condition, the open duct velocity was 22.02 feet per second. Since the model center-line flow length (vertical configurations) was 3.75 feet, Figure 24 indicates that a test cell flow length of 120 feet was simulated, and this was considered typical of many sea level test facilities. Figure 24 shows that at full engine power and zero cell augmentation the power source had to be capable of producing a duct velocity of 8.8 feet per second. Test data included in the computer output section of this report indicate that this value was closely approached by the selected blower unit when connected directly to the horizontal engine duct. Power system layout is illustrated in Fig. 25, and system performance is evaluated in Section VI (A).

#### D. INSTRUMENTATION

##### 1. Requirements

The correlation of inlet configuration and distortion required information on the existing distortion, the model operating condition, and the makeup of the inlet. A survey of the compressor face velocity profile could have been made either with a positionally fixed set of probes or a single probe which could have been located at varying positions. Any of the numerous velocity measuring systems designed for subsonic flow could have been utilized, and the choice was dependent upon the aim of the test program. Investigation of dynamic distortion effects would require response time consistent with the anticipated fluctuations. This investigation, being confined to the effect of



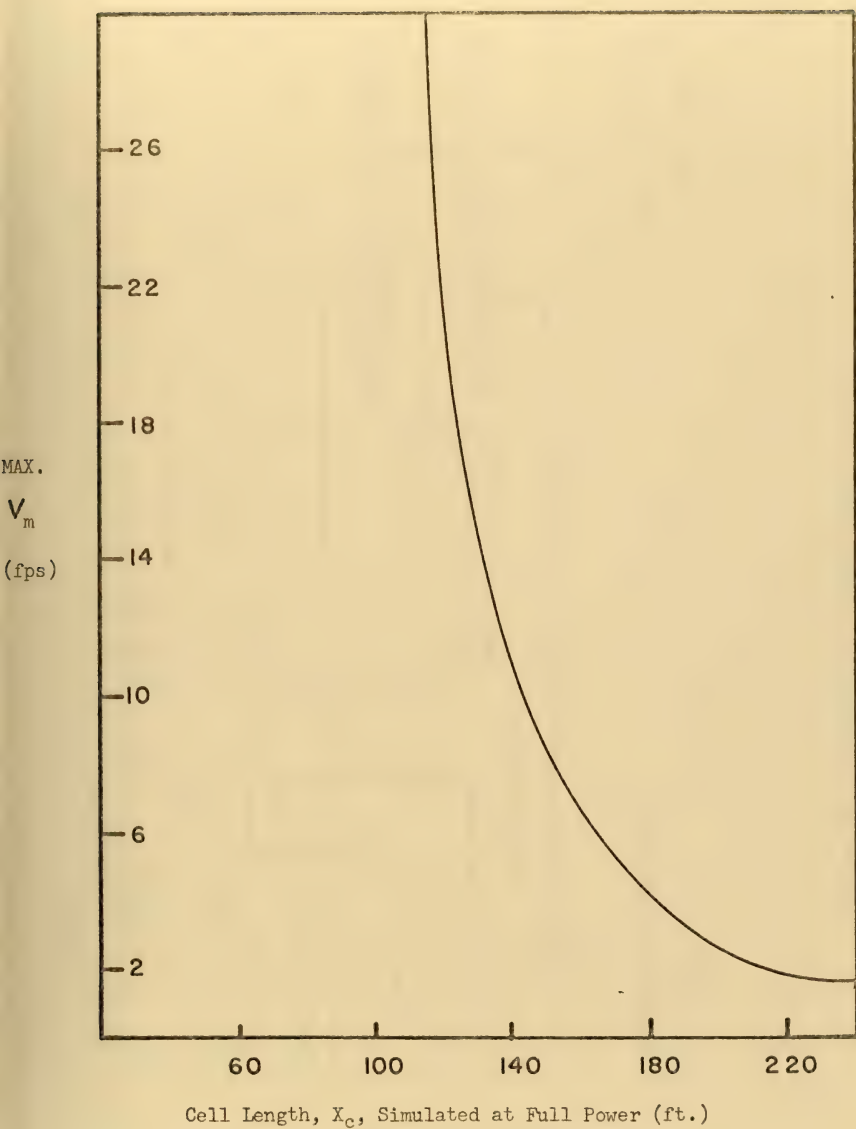


Figure 24. THE VARIATION OF SIMULATED LENGTH WITH  
MAXIMUM MODEL FLOW VELOCITY



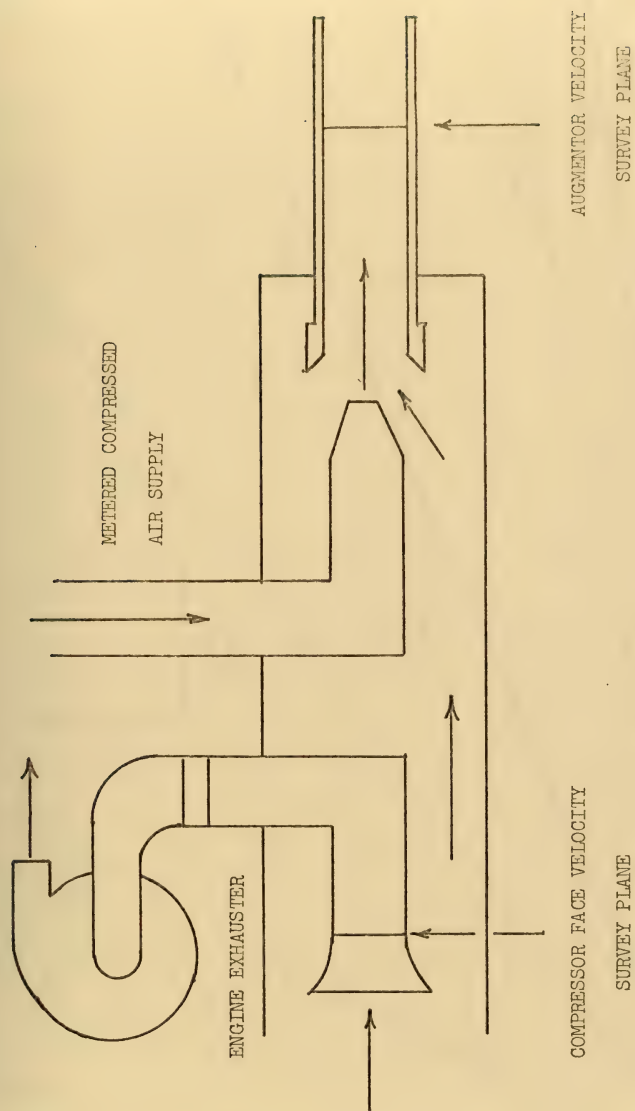


Figure 25. AUGMENTED FLOW POWER SYSTEM LAYOUT





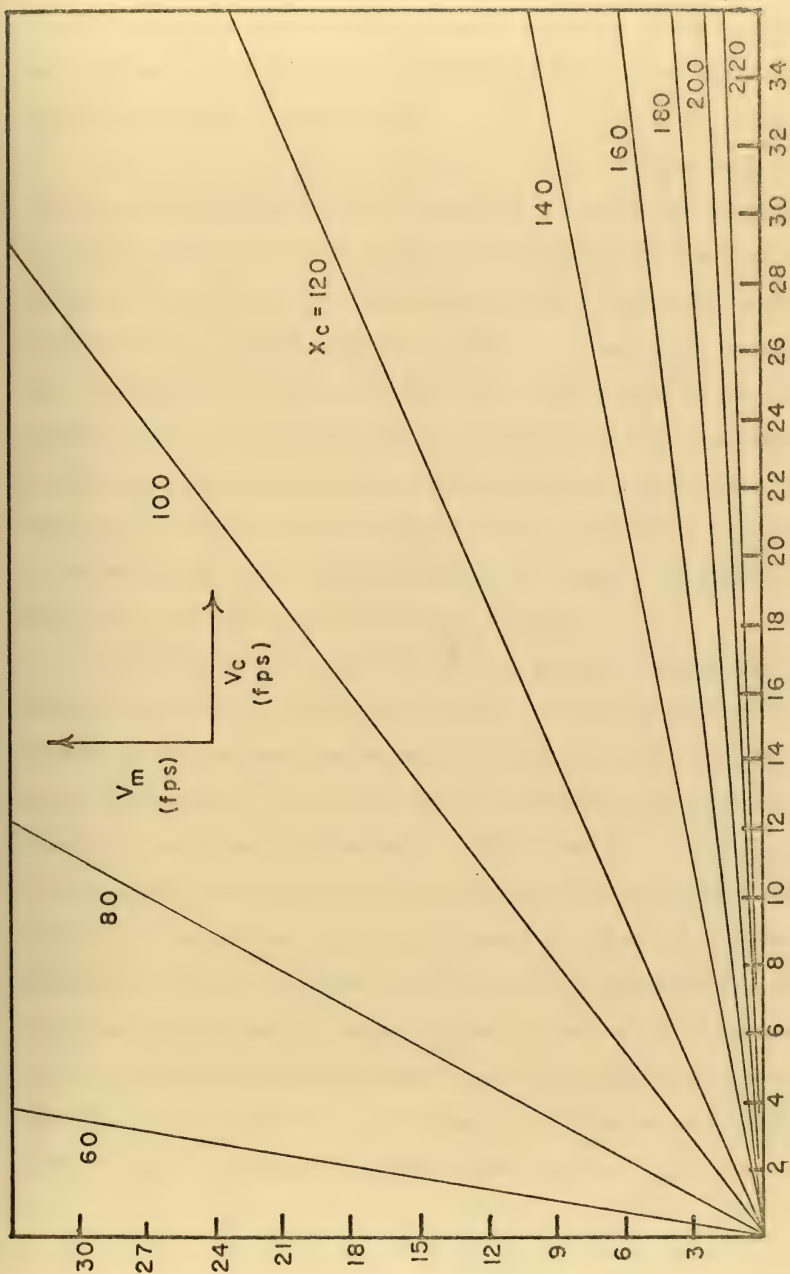


Figure 26. VARIATION OF LENGTH SCALE WITH TEST CELL VELOCITY



steady distortion, made the use of slower responding instruments possible and eliminated the requirement for simultaneous measurement of model vibration stressed by Jansen in Ref. 15.

Practical considerations entered the selection problem since large numbers of tests were anticipated, and the total time required to complete the program was largely dependent on the effort required to record the distortion data for each configuration. While it was possible that provision of a measurement probe which could be located at any position within the inlet could contribute to a full analysis of the flow system, this was considered impractical in tests for direct engineering application. The number of runs required and the desire to reduce data acquisition time to a minimum suggested that a fixed survey rake located at the compressor face would have definite advantages over a single probe which had to be relocated between readings.

Either pitot static probes or those using electromagnetic pressure transducers are well suited to the requirements of a subsonic velocity survey and were considered for use in the model. The pitot static system offered lower cost, and the transducers were more easily adapted to use in an automated data recording system. In addition to the measurement of distortion, it was necessary that instrumentation be provided for the determination of cell mass flow rates. This would establish the simulated engine power level and the effective cell augmentation ratio. Practical considerations of cost and speed of operation confined the selection to standard methods suited to the low speed, low flow rate anticipated. The instrumentation selected as a result of these factors is described in the following section.



## 2. Description

For the determination of distortion twenty five total pressure probes were built into the model engine. Probe positions were selected to permit the measurement of both radial and circumferential distortion. Location and identification are detailed in Figure 27. Initially, alignment was parallel to the engine axis. This was adjusted for individual inlet configurations where evidence of misalignment was encountered in the form of excessive total pressure difference between adjacent probes. The effect of the velocity survey rake assembly on the flow was considered and limited the number and size of the probes employed. The twenty five probes at the compressor face had an outside diameter of one eighth inch so that total blockage area was 0.202 square inches. This was 1.6 per cent of the total flow area and was considered consistent with the blockage of the inlet guide vanes in current engines. At the plane of the probe stems, the blockage was 1.125 square inches or 9 per cent, and this is less than the solidity of most first stage compressor stators. Two static pressure taps were inserted on opposite sides of the engine duct at the plane of the velocity survey. While the assumption of uniform static pressure across the duct was borne out in the observed data, the individual static pressure values were associated with the closest total pressure heads for reduction of the data to velocity. This arrangement considerably simplified construction of the survey rake since the assembly of twenty five pitot static probes of the required shape would have been a formidable task.

Total and static probes were connected with flexible plastic tubing to an inclined manometer board, so marked as to permit a resolution of 0.02 inches of water in gage pressure. Since the maximum



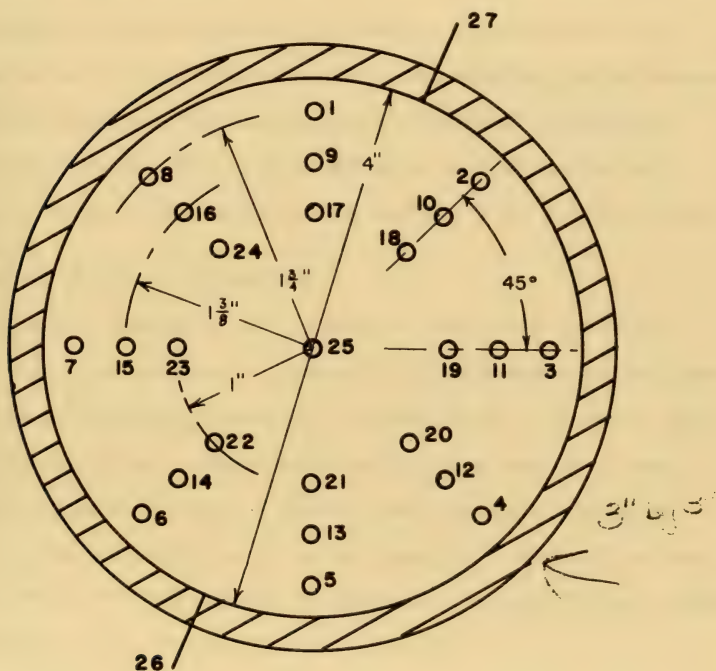
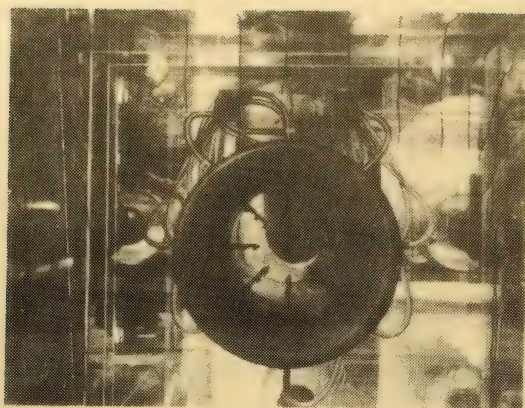


Figure 27. THE ARRANGEMENT OF COMPRESSOR FACE INSTRUMENTATION







anticipated compressor face Mach number was less than 0.2, it was possible to assume atmospheric density at the plane of the velocity survey. The pressure information was thus sufficient to determine the engine mass flow rate. A variety of methods for the averaging of the velocity data were used and are detailed in the following chapter.

Additional instrumentation consisted of static pressure taps in the duct walls foreward of the engine bellmouth for the determination of cell depression and that associated with the augmentor flow system. A standard throttling plate and required instrumentation were installed in the high pressure supply line, and provisions were made in the augmentor tubes for the operation of velocity surveying traverses. Prior to the testing of fully assembled inlet models, instrumentation was installed in the vertical inlet stack to permit velocity profile measurement at that position. This instrumentation consisted of two pitot static probes inserted through the stack walls at right angles and secured in a manner which permitted adjustment of their extended length.

#### E. SELECTION OF TEST CONFIGURATIONS

With the interchangeable duct components constructed for this investigation, it was possible to construct 3240 different inlet configurations without introducing frames for different kinds of screens. Each of these configurations could be operated at a wide variety of power levels and augmentation ratios. Since it was necessary to limit the duration of the testing phase, it was not possible to test all, or even a large portion, of these possible arrangements. Several factors affected the selection of the configurations to be tested.

In the construction of the model components the vertical inlet stack and the inlet caps were completed first, and during the construction of



the other components, tests were made to determine the effect of the inlet cap on the initial velocity profile in the vertical duct. As a result of these tests, it was concluded that sufficient difference existed in these profiles to substantially effect the overall inlet performance

An additional constraint was the fact that the design and fabrication of the augmentation system was more complex and time consuming than that of the inlet components. It was thus possible to test first those configurations not requiring augmentation. Also since the major difference existing in current test cell designs, other than their augmentation, is the presence or absence of turning vanes, the initial test phase was divided into two portions.

The horizontal inlet configurations were tested first with the various acoustic treatments, engine power levels and zero augmentation flow. The vertical inlets were then tested for all combinations of acoustic treatment and inlet caps. These were tested at full and reduced power levels though the observed trend of increasing distortion with increasing flow rate was found to be consistent throughout this phase. The effect of installed flow straightener sections was studied through their addition to previously tested configurations.

This full set of vertical configurations was then retested with each of four different combinations of turning vanes, still without augmenting flow. Then, from the analysis of the data accumulated to this point, configurations were selected for testing with nonzero augmentation ratios. The majority of those selected were at the extremes of the distortion spectrum observed during the tests of unaugmented configurations. Additional configurations were selected to insure the inclusion of all



components and each major configuration type. This was considered necessary since configurations composed of components which generated little distortion at low flow rates might show disproportionately higher distortion potentials if an increase in the flow rate caused separation of the flow to occur in some component. A total of 213 different configurations were tested and an additional 22 test runs were made to check on the repeatability of the test results.



## V. INLET MODEL TEST PROCEDURES

### A. CONFIGURATION IDENTIFICATION

Each inlet model test was identified by a ten digit code number which indicated the included components, their arrangement, and the settings of the engine and augmentor power supplies. The code used is indicated in Table II. The use of numerical identification numbers facilitated computer sorting and grouping of the processed test data and permitted changes and additions to be made without making it necessary to reidentify the data sets previously collected. This was a significant advantage since as the test data was accumulated, it became possible to identify significant distortion sources and refine the test parameters to investigate the persistence of these characteristics over a range of similar configuration and operational conditions.

### B. FLOW VISUALIZATION METHODS

An initial attempt was made to secure a photographic record of smoke traces injected into the inlet of the model. The record of streamline behavior provided by these records would have been of value if the deflection of an initially uniform flow by the various inlet components could have been correlated with the total distortion of the engine air supply. The turbulent nature of the flow in the inlet was confirmed by the observation of the almost immediate and complete diffusion of the initially thin, uniform smoke streams. No smoke source tested provided a stream trace which persisted more than three inches into the inlet. It was therefore necessary to utilize alternate means of visualization.





Table II. CONFIGURATION IDENTIFICATION

Configuration Codes: ABCD.EGFHIJ

A INLET	B INLET CAP	C ACOUSTICS	D ACOUS. POSIT.
1 vertical	1 none	1 none	1 before turn, transverse
2 horizontal	2 faired	2 flat baff.	2 after turn
3 none	3 bi-direct.	3 staggered baffles	3 none
4 vert. w/o stack	4 flat plate	4 tubular	4 before turn, axial
	5 bi-direct. sideways	5 stag. baff. X-ways	5 top of stack
E TURN VANES	F FLOW GDS.	G ENG/BELL	H AUGMENT.
1 none	1 none	1 neither	1 none (end plate)
2 one (#3)	7 hex section	2 eng w/o bell	2 none poss.
3 four		3 eng+bell	3 low
4 seven			4 medium
5 one (#5)			5 high
6 one (#1)			6 zero
7 four in turn #2			
8 one (#3) in turn #2			
9 seven in turn #2			
I POWER	J ENGINE PWR		
1 test sect-blower	1 max		
2 eng-blower	2 mid		
3 eng+aug-blower	3 min		
4 dual mode			



Yarn tufts were secured to the interior surface of the inlet duct forward of the engine in the test section and in upstream areas not occupied by the acoustic treatment models. In another effort to provide some indication of streamline positions lengths of light weight black thread were fed into the inlet from various positions and extended through the inlet components to the compressor face. At low flow rates the flow velocity was insufficient to support the weight of the tracer, and it was consistently carried toward the bottom of the duct from all entry positions.

At higher flow rates the turbulence of the flow was such that the results of this tracing were time dependent with different paths being followed from identical entry positions. It was not possible to produce permanent streamline position records, but useful qualitative information was obtained in this way. Through observation of trace motion, particularly the portion close to the free tip of the thread, it was possible to obtain comparative information about the scale of the turbulent macro-eddies generated by the components of the inlet duct. This information was utilized in the development of the correlation method and provided some feeling for the nature of the interaction of the various duct components. This trace method was also of value in the alignment of the total pressure probes at the compressor face and in confirming that the presence of the survey rake in the engine did not alter the bare engine flow characteristics to any observable degree. The use of this technique is recommended for future model test programs since it is of minimal cost and required only that caution be exercised to prevent ingestion of the trace by the power source.



## C. TEST METHODS

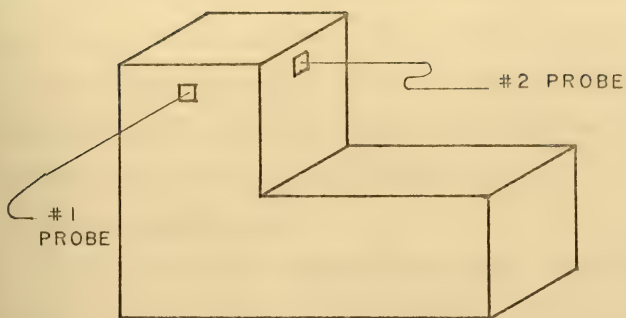
### 1. Inlet Flow Velocity Profiles

For these tests the flow straightener, turning corner, and vertical stack components were assembled with the downstream end of the straightener section connected directly to a suction power source. Each of the four inlet caps was tested at three flow rates. For each operating condition, two pitot static probes were traversed perpendicularly across the inlet in a plane level with the top of the vertical stack. At each of the positions shown in Figure 28 the manometer displacement of the total and static pressure ports were recorded. Prevailing atmospheric pressure and ambient temperature were recorded from standard laboratory instruments at the beginning and end of each test period.

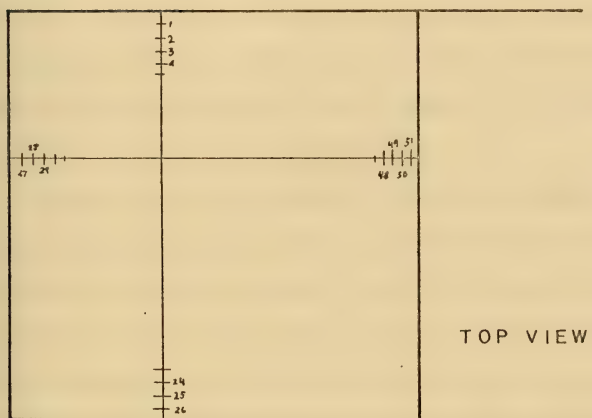
### 2. Distortion Baseline Tests

With the instrumented engine model installed in the test section and connected to the blower intake, the upstream duct components were removed. With the power set at various levels the manometer deflections for the twenty five total and two static pressure ports were recorded. Initial tests were made with the test section and power source supported in the center of a solid laboratory table. With the bellmouth in place on the engine, the velocity profile observed clearly indicated that the table surface influenced the velocity in the lower third of the test plane. With the test section reoriented to overhang the table edge, this effect was removed. With this arrangement, uniform velocity was observed at all power levels within the 0.02 in.  $H_2O$  accuracy of the inclined water manometer system. These tests also served to provide calibration of the power source regulator for all unaugmented configuration tests.





PROBE POSITIONS



DATA POSITIONS

Figure 28. INLET VELOCITY SURVEY PLAN





When construction of the dual power source test section was completed, these tests were repeated with the additional ducting in place between engine model and blower. This provided calibration of the power supply for augmented tests and confirmed the presumption that the necessary  $90^{\circ}$  turn in the engine model ducting would not observably affect the uniformity of the test plane flow.

### 3. Non-Augmented Tests

Each of the inlet configurations tested without augmented flow was assembled with a duct end plate in place at the downstream end of the test section component. The power source blower was throttled in accordance with the calibration obtained during the baseline tests and activated. When uniform flow had been established (manometer displacements constant), the data sheet shown in Figure 29 was completed. Laboratory pressure and temperature were recorded from standard instruments.

### 4. Tests of Augmented Configurations

In addition to the procedure followed for those configurations without augmentation, these tests required measurement of the total mass flow through the augmentor exhaust duct and the mass flow rate of the air supplied to the ejector nozzle. Bailey in Ref. 4<sup>1</sup> supplies a complete description of the methods used in these measurements. His data processing method produced a flow rate, in pounds per second, of inlet flow by-passing the engine bellmouth, and this was entered on the data record prior to processing of the distortion data.

## D. DATA PROCESSING METHODS

### 1. Goals Established

The most general aim of the processing methods developed during this investigation was to establish the basis for a consistent correlation



DATE \_\_\_\_\_

COMPRESSOR FACE	Patm - Ptot	CONFIGURATION CODE				
		PROBE 1				
		2				
		3				
		4				
		5				
		6				
		7				
		8				
		9				
		10				
		11				
		12				
		13				
		14				
		15				
		16				
		17				
		18				
		19				
		20				
		21				
		22				
		23				
		24				
	25					
	Patm-Ps					
26						
	27					
Cell Depression						
Upstream Tufts						
Downstream Tufts						
Test Plane Dynamics						

Patm \_\_\_\_\_ in. Hg      Tatm \_\_\_\_\_ °F      Maug \_\_\_\_\_ lbm/sec

Figure 29. INLET TEST DATA SHEET



between inlet configuration and engine distortion level. This imposed several requirements on the selection of processing techniques. Since many different methods were available and no prediction could be made as to which would most readily provide the desired correlation, a primary requirement for the processing system was that it be able to use all the available methods and compare the results. This requirement and that of limited project completion time implied the necessity for machine processing of the collected data. The information from the test data sheets was transferred to punch cards and processed by the programs described in the following sections. This technique met the additional requirement which is inherent in correlation methods; that is, the repeated processing of large amounts of data as different correlation parameters were tested.

## 2. Vertical Inlet Velocity Survey

The program developed for the processing of this survey data is included in the computer program section of this report. This program was written in the FORTRAN IV language for the Naval Postgraduate School's IBM system 360 and had as its primary aim the evaluation of inlet cap effect on initial inlet velocity profile. Secondly, it was desired to evaluate the proposal that one or two pitot static probes properly located in the vertical inlet stack would make accurate determination of total inlet mass flow rate possible.

The average velocity measured along the line of each probe traverse was computed directly from manometer readings of  $P_t - P_s$  and the assumption of constant density. This required the averaging of the velocity at each adjacent pair of measuring stations and the weighting of this average value with the lengthwise separation of the points.



These length weighted velocities were then summed and divided by the total length of the traverse to obtain a quantity identified within the program as the "slice average velocity." The velocity profile obtained in this manner was then adjusted by a constant factor, the value of which was determined as that necessary to cause the adjusted value at the point of intersection with the second trace to equal the observed velocity at that point. Figure 30 schematically illustrates this process. In this manner slice average velocities were obtained on both sides of the measured one, one for each data point on the second crosswise trace. These slice averages were in turn averaged and weighted by the lateral distance between sections and then divided by the total flow area to obtain the final average flow velocity.

This complete procedure was then repeated with the two sets of survey data points in opposite roles with the results of both calculations being presented in tabular form for comparison. Figure 31 shows a typical pair of measured profiles. The processed data was also examined in an attempt to select probe positions, which for each inlet cap accurately measured a velocity near the calculated average at all power levels. As the power source used in this test program was different than that to be used in the testing of complete inlet models, no attempt was made to calibrate the blower throttle position with mass flow.

### 3. Distortion Tests

This program accepted the information from the data sheet shown in Figure 29. All recorded manometer data was converted to absolute pressure, and the minimum and maximum total pressure readings were identified. The average total pressure at the compressor face was





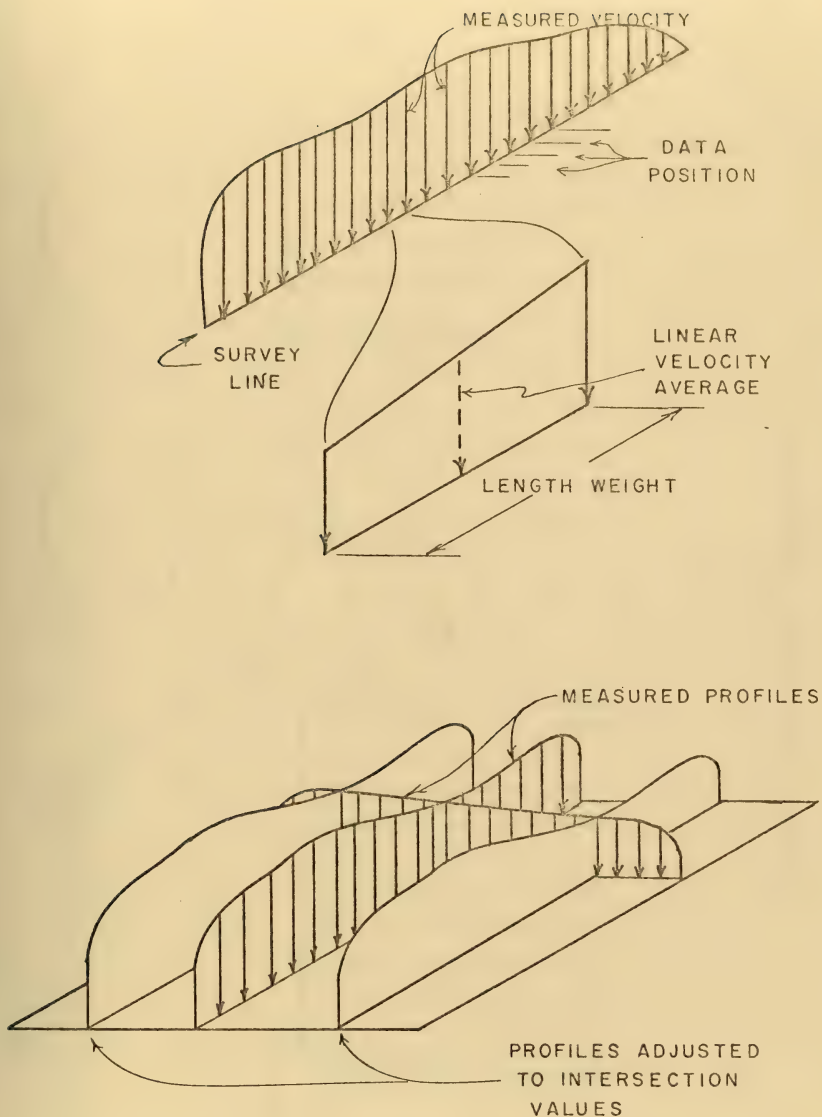


Figure 30. INLET VELOCITY AVERAGING PROCEDURE



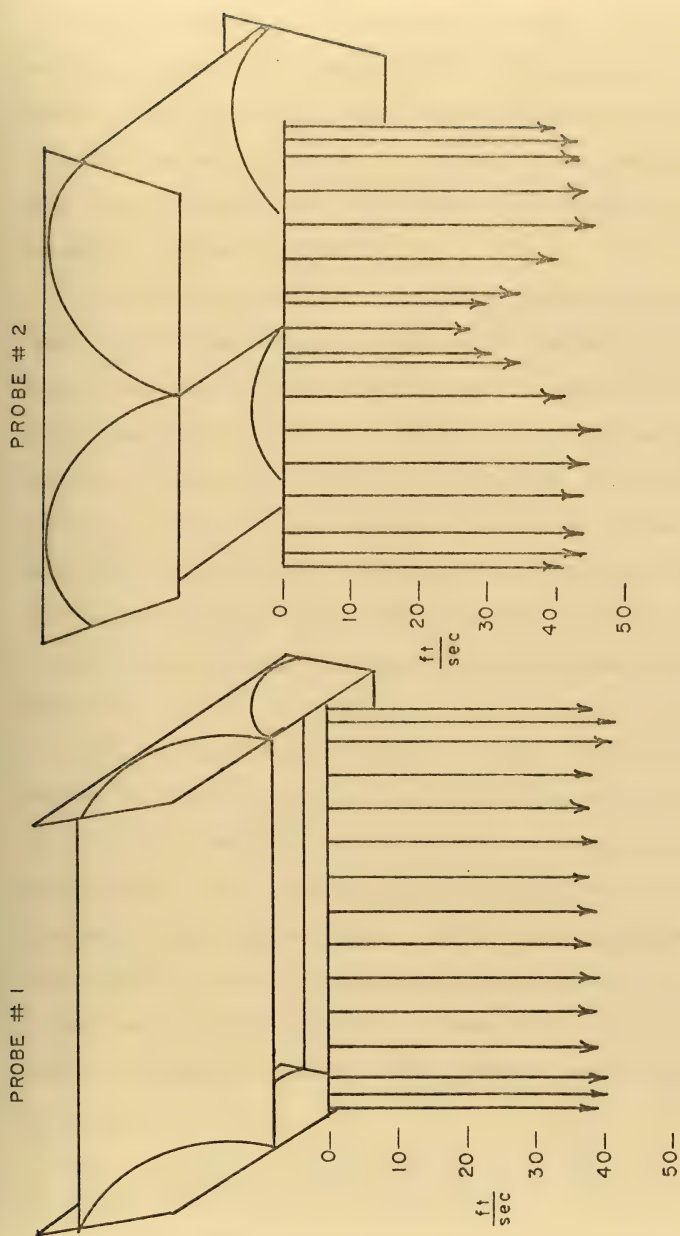


Figure 31. TYPICAL INLET VELOCITY SURVEYS



computed by numerical and area weighted averaging, and the mass flow averaging technique which Ferguson [Ref. 27] demonstrates to be the only theoretically valid method. This computation also provided the average velocities and mass flow rates for the engine using the static pressure data from the probe nearest to each total pressure position and the assumption of atmospheric density.

Average total pressures for each  $45^\circ$  sector of the compressor face plane was then evaluated using mass flow weighting. If any sector was more than one per cent below the overall average in total pressure, it was identified as spoiled. Adjacent sectors were then examined to determine the angular extent of the low pressure area by linear interpolation of the sector average values.<sup>1</sup> With this information the Naval Air Propulsion Test Center's circumferential distortion factor used by the Arnold Engineering Development Center [Ref. 36] was also evaluated at this point along with other common distortion measures shown in Table III.

These factors were considered to apply to a typical current turbojet (first stage compressor rpm of 8320 and high pressure stages at 14,154 rpm). Where known limits existed for the initiation of engine stall or surge, these distortion indices were evaluated as satisfactory for this typical engine. If the inlet configuration produced unsatisfactory distortion levels, the limiting type was identified (either radial or circumferential). Where the limiting distortion was radial, the program indicated whether the stall would originate in the

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<sup>1</sup> This procedure is identical to that used in Ref. 21 except that  $30^\circ$  sectors were used in that investigation.

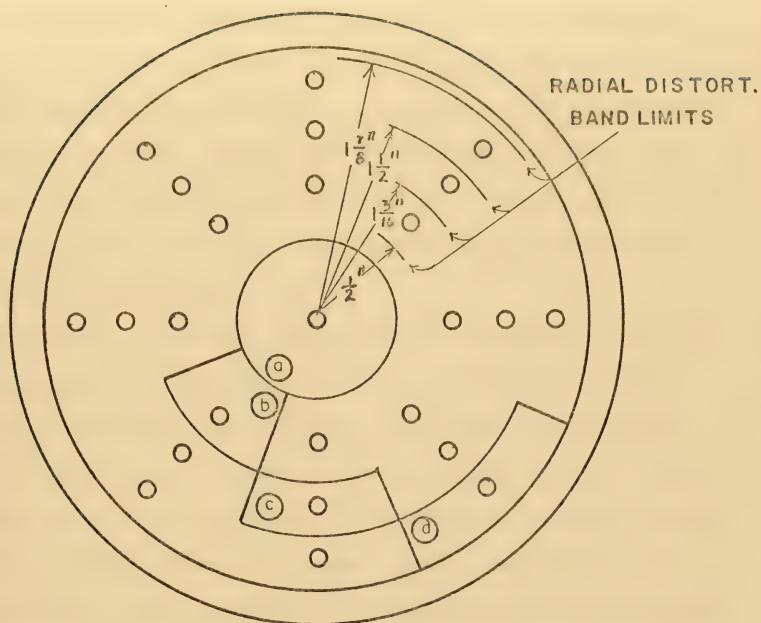


Table III. MEASURES OF DISTORTION

NAME	SOURCE	DEFINITION
K	Ref. 11	$\frac{[(\bar{\theta}/2\pi)(q/P)^{1/2}]_{\text{ref.}}}{(q/P)^{1/2}/(\bar{q}/\bar{P})^{1/2}}$ <p>Where <math>\bar{\theta} \equiv</math> radial extent of spoiled sector.</p>
K <sub>r</sub>	Ref. 42	$\left\{ (\bar{r}/r_0) (r_2 - r_1) / [r_2 Z_2(r) - r_1 Z_1(r)] \right\} \times$ $\left[ \left\{ [1 - (\Delta P/\bar{P})] / \sqrt{(q/P)/(q/P)} \right\} - 1 \right] \times$ $[1 + (q/\delta P)]$ <p>where Z is a complex function of position formed from eigenvalues of appropriate momentum equations and a linear combination of Bessel functions of the first and second kinds.</p>
K <sub>D</sub>	Refs. 7 and 10	$\frac{100 \sum_n \left[ \left( \frac{P_{\text{ring(avg)}} - P_{\text{ring(min)}}}{P_{\text{ring(avg)}}} \right) \bar{\theta}_{\text{ring}} C_{\text{ring}} \right]}{\sum C_{\text{ring}}}$
D <sub>I</sub>	Ref. 43	$(P_{T \text{ max}} - P_{T \text{ min}}) / P_{T \text{ avg}}$
D <sub>I2</sub>	Ref. 43	$(P_{T \text{ avg}} - P_{T \text{ min}}) / P_{T \text{ avg}}$
D <sub>I3</sub>	Ref. 43	$(P_{T \text{ max}} - P_{T \text{ min}}) / P_{T \text{ avg}}$







PROBE	(a)	0.5964 in <sup>2</sup>
AREAS	(b)	0.38935 in <sup>2</sup>
(minus probe blockage)	(c)	0.4399 in <sup>2</sup>
	(d)	0.7698 in <sup>2</sup>

Figure 32. SURVEY PLANE SUBDIVISIONS



the hub or tip area of the compressor blades. When circumferential distortion caused unsatisfactory performance, the program output included the rpm below which the compressor could operate unstalled in the inlet being evaluated [Ref. 417]. Intermediate values required in the calculation procedure and all results were printed for each configuration. At the end of each processing run, a summary table was produced which had the form of the tables included in this report in the computer output section.

A modified form of this program was also developed which eliminated the complete data for each configuration and produced a punch card output containing the summary data. Two sorting routines were then used to assist in the organization of the test data. Both sorted the summary data cards and produced tables containing this data arranged in sets having configuration code numbers with a common digit in any desired position. This permitted the test results to be collected into groups having common inlet components or operating conditions.

The sorting programs differed in the ordering of the tabular data. The first produced tables in which the configuration code numbers were arranged in numerical order. The second type of tables were arranged in order of increasing distortion level. Primary ordering was dependent on the value of the NAPTC circumferential distortion index. Where differences in this value were not significant, the data lines were ordered using values of the radial index. Both included optional commands to permit the production of complete summary tables ordered in the same manner as the grouped ones. The numerically ordered tables permitted rapid location of the data for any desired configuration number and grouped the results of repeated tests for comparison. Those



ordered by distortion level simplified the selection of high and low distortion configurations and components. Ordering of the test data in this manner was instrumental in permitting rapid testing of the various proposed correlation methods since any system which radically altered the order of the configurations could be discontinued.



## VI. TEST RESULTS

### A. MODEL PERFORMANCE

Construction methods and materials proved to be satisfactory in all respects. Two inlet components were damaged during the test program, but repairs required minimum time and were effected without alteration of the duct dimensions or finish. Measurable distortion of the duct components occurred only during the tests in which the cell depression exceeded two inches of water. Maximum deflection was less than one per cent of duct height, and no attempt was made to correct the data for the three tests in which depression in excess of two inches was observed.

The jet pump exhaust simulator provided more than adequate augmentation flow in the model, but the number of variables (augmentor geometry and placement, cell depression, and primary flow rate) controlling this flow rate was such that it was not possible to predict in advance the augmentation ratio which would exist during each run. This resulted in variations between tests which precluded the possible quantitative evaluation of the effect of augmentation on distortion level.

The limited capacity of the suction source placed an additional limitation on the variety of configurations tested. The losses produced in the ducting between blower and compressor face, when the model was assembled for augmented flow tests, were of a magnitude to produce an engine power level similar to that produced by direct connection of the engine to the blower with the maximum flow restrictor in place. Future extension of the test results reported here will require the addition of a more powerful and directly adjustable suction power source.





Performance of the test instrumentation was acceptable. The automation of the data processing task would have made the use of a manometer board with variable inclination readily feasible and would have improved the accuracy of the test data by providing an adjustment for the wide range of pressures encountered. No attempt was made to directly assess the effect of test section blockage by the instrumentation leads; but their effect could be observed during flow visualization, and streamlining of this area should be considered in future tests.

The design of the model used in this experimental investigation was fundamentally sound and provided reproduceable data of the required type and quantity. The time required per test run was considered excessive; approximately one hour for non-augmented configurations and two for those in which both power systems were required. This was due primarily to the necessity for hand recording of the data and subsequent transfer to punched cards. Extensive future use of this model should involve the installation of at least semi-automatic data acquisition equipment.

## B. COMPONENT PERFORMANCE

### 1. Acoustic Treatments

Of the models tested, the tubular type proved to be the least satisfactory with only 5 of 27 configurations exhibiting acceptable distortion levels. All of those which were satisfactory required that the tubular treatment be located in the horizontal flow straightening section; a highly impractical arrangement for actual test cells. Additional testing of this treatment with varied flow length and blockage models will be required before it is completely evaluated, but initially it does not appear to be competitive. It was not possible to discriminate



clearly between the other tested acoustic alternatives as they exhibited approximately equal percentages of satisfactory performances.

## 2. Inlet Caps

Through the testing of numerous configurations which differed only in the type of inlet cap, it was possible to make a fairly clear determination of their effect on inlet distortion. In general, the faired cap produced minimum distortion at the compressor face, followed by bi-directional, open end, and flat plate caps. This order was consistent (within the accuracy of measurement) for all configurations in which the acoustic treatment was located in the vertical stack portion of the inlet duct. For those vertical configurations without acoustic components (the lined wall concept of Appendix C) or those with the treatment in the horizontal duct section, cap performance was less predictable and highly dependent on the type of turning vanes included. With four or seven present in the duct bend, the performance of the open ended vertical inlet was greatly improved. Seven turning vanes acted with the uncapped inlet to provide less distortion than with any of the other caps, regardless of acoustic type. The flat plate cap also improved the uniformity of the flow produced when at least one vane was present in the corner. With four or seven vanes in use, this cap was superior in performance to the bi-directional one. Using one or three vanes, it was better than the open inlet though not quite equal to the bi-directional.

## 3. Duct Orientation

The effect of duct shape was the clearest and most easily predictable. Only one of eight horizontal inlet configurations (that without flow straighteners and with the staggered acoustic baffles



inserted horizontally) was found to be unsatisfactory. Conversely, 29 of the  $3\frac{1}{2}$  triple turn configurations exhibited unsatisfactory distortion levels. Although it was not possible to test this arrangement with turning vanes in all three corners, several combinations of vane numbers and positions were investigated without finding one which could reduce distortion to an acceptable level over a range of flow rates. Vertical inlet configurations were of intermediate value with the distortion level being dependent upon the other duct components. No vertical configuration was better than the best horizontal one or worse than the worst three-turn model.

## C. CORRELATION METHODS

### 1. Distortion Measurement

The first decision necessary in the establishment of a correlation method was the selection of the distortion measurement index to be used. Any of those listed in Table III could have been selected. The choice was made on the basis of the evaluation of these and other indices reported by Brunda and Boytos in Refs. 42 and 44. It was their conclusion, based on extensive experimental research, that of the available distortion indicators only the NAPTC circumferential and radial indices could be consistently related to engine performance. They additionally determined that for the majority of current and future jet engines, performance is most often limited by the extent of the circumferential distortion. The NAPTC circumferential distortion factor was selected as the measure of distortion level with which inlet configuration would be correlated.



## 2. Inlet Correlation Parameters

### a. Alternatives

It must be considered possible that the distortion level measured at the engine compressor face of a jet engine might be related to any of the following factors either singularly or in any combination:

1. Average flow length.
2. Total wetted area.
3. Difference between maximum and minimum streamline length from inlet cap to compressor face.
4. Number of distinct wetted surfaces.
5. Total degrees of turning.
6. Percentage of duct length obstructed.
7. Maximum local velocity or position.
8. Separated flow volume or area.
9. Number, volume, or surface area of cross duct obstructions.
10. Engine position relative to duct center.
11. Ratio of duct height to width.
12. Number, position, or size of turning vanes.
13. Shape, length, or blockage of flow straighteners.
14. Shape of inlet cap.
15. Relative component lengths or areas.
16. Number and ratio of convergent-divergent flow sections.
17. Surface roughness.
18. Position or shape of screens.
19. Engine or augmentation flow rates.
20. Augmentation ratio.





21. Engine bellmouth shape or size.
22. Cell depression.
23. Exhaust back pressure.
24. Size or ratio of turn radii.

b. The Selected Correlation Method

Eleven separate correlations were attempted between individual configuration characteristics included in the above list and the selected distortion indices. In none of these was there evidence of a consistent relationship. As a result, the following rational approach to the analysis of the interactive effects was developed. This initial correlation development was confined exclusively to vertical inlet configurations. This is an extension of the method used in Ref. 15 for the correlation of aircraft inlet effects.

The components considered were the inlet cap, the type of acoustic treatment, its position, and the number of turning vanes present. For each of these components, distortion producing contributions were considered possible from seven characteristic properties:

1. Distance from the upstream component.
2. Component length.
3. Percentage of duct area reduction.
4. Number of flow subdivisions produced.
5. Degrees of turning.
6. Alignment with upstream components.
7. Alignment with next downstream component.

For each type of duct component, the available alternative models were rated according to the possible contribution of each of the above factors. The initially assigned values are shown in Table IV. The configuration



Table IV. INITIAL PENALTY WEIGHTS

COMP CODE	DIST	LTH	BL	#DIV	°T	AL UP	AL DW
B = 1	0	2	0	4	45	0	0
2	0	0	0	3	20	0	0
3	0	3	10	2	100	0	4
4	0	4	40	4	135	0	0
5	0	3	10	2	100	0	2
C = 1	0	8	0	0	0	0	0
2	0	8	50	12	15	0	0
3	0	8	60	24	30	0	0
4	0	3	75	64	45	0	0
5	0	8	60	24	30	2	2
D = 1	16	5	0	0	0	0	10
2	8	0	0	0	0	0	5
3	2	0	0	0	0	0	0
4	16	5	0	0	0	2	5
5	16	0	0	0	0	0	2
E = 1	0	3	0	0	90	5	20
2	5	0	4	2	90	5	0
3	5	4	16	5	90	5	10
4	15	5	28	8	90	5	10
5	10	2	4	2	90	5	10
6	15	1	4	2	90	5	0
COL. TOT.	108	72	401	208	1060	32	71
SIGNIF.	80	70	100	20	60	40	30
FACTOR	.75	.97	.25	.10	.0566	.8	.422



component codes used in this table are the same as those established in Table II. These values were considered penalty factors with higher values designating greater distortion potentials. To normalize these penalty values an initial estimate was made of the relative importance of the seven selected distortion characteristics. This estimate is shown in Table IV as the SIGNIFICANCE line. The multiplication factors necessary to reduce the column totals to the desired significance level were determined and applied to each of the penalty factors in that column. This produced the adjusted factors shown in Table V. The total estimated penalty factor for each configuration component was then available in the ROW TOTAL column.

These component factors were applied to a random selection of configuration codes, first through the addition of the penalty weights and secondly by the multiplication of these values. The selected configurations were then ordered according to their total penalty value and the resulting ranking compared with that produced by sorting the same configurations according to distortion level. These ordered lists were examined to discover components or combinations of them which were present in configurations found to be out of order. The distortion penalty weights assigned to these components were then adjusted by the amount necessary to correct this order. The penalty totals for all configurations required re-evaluation after each such adjustment. When excessive corrections were applied, the resulting disorder was often greater after correction than before.

This process was then repeated with the object of producing a set of component penalty weights which when either added or multiplied together ordered the configurations according to their distortion level.



Table V. NORMALIZED PENALTY WEIGHTS

COMP CODE	ROW TOT	DIST	LTH	%BL	#DIV	$\sigma_T$	AL UP	AL DW
B = 1	4.94	0	2	0	.4	2.54	0	0
2	1.43	0	0	0	.3	1.13	0	0
3	13.06	0	3	2.5	.2	5.66	0	1.7
4	21.9	0	4	10	.4	7.5	0	0
5	12.2	0	3	2.5	.2	5.66	0	.844
C = 1	8.0	0	8	0	0	0	0	0
2	22.55	0	8	12.5	1.2	.85	0	0
3	27.1	0	8	15	2.4	1.7	0	0
4	30.69	0	3	18.75	6.4	2.54	0	0
5	29.54	0	8	15	2.4	1.7	1.6	.84
D = 1	21.22	11.8	5	0	0	0	0	4.22
2	8.11	5.96	0	0	0	0	0	2.11
3	1.5	1.5	0	0	0	0	0	0
4	20.71	11.8	5	0	0	0	1.6	2.11
5	12.84	11.8	0	0	0	0	0	.84
E = 1	20.54	0	3	0	9	5.1	4	8.44
2	14.05	3.75	0	1	.2	5.1	4	0
3	25.57	3.75	4	4	.5	5.1	4	4.22
4	37.37	11.25	5	7	.8	5.1	4	4.22
5	19.8	7.5	2	1	.2	5.1	4	0
6	24.66	11.25	1	1	.3	5.1	4	2.11





In applying this method it became apparent that the summation technique required fewer iterations, and it was adopted as the preferred technique. Multiplication totals were kept for reference, but iteration was terminated once the additively ordered list matched the distortion ranking.

Beginning with a set of 10 vertical configurations, the ordering was completed after 5 iterative adjustments of the penalty weights. Ten additional configurations were then added to the ordered set and the adjustment procedure repeated if necessary. This procedure was continued until all of the 176 vertical configurations tested were included in the ordered set.

Several times during the execution of this phase progress was arrested when a cycle of repetitive adjustments were established. In some of these cases it was possible to identify one or more of the most recently added configurations which were responsible for the untracking of orderly progress. These suspect configurations were re-assembled in the lab and the distortion measurement tests repeated. In 12 such cases significant changes in distortion level were observed. If a second retest confirmed this new result, the original data was deleted from the summary file and replaced with the improved measurement.

In 8 of the required retests the originally measured distortion level was confirmed. These configurations were assigned an EXCEPTION label and examined after each subsequent adjustment of penalty values. If this examination found the new set of weights ordered this configuration properly, it was returned to the ordered set. Otherwise, it remained in the exception file and was not considered in determining the acceptability of subsequent weight sets.



It was recognized that measurement accuracy was a necessary consideration in the distortion order ranking. Appendix B demonstrates that the assumed limit of total pressure measurement accuracy of 0.01 inches of water represents a possible variation of from three to eleven rank positions depending upon overall position in the distortion spectrum. Thus, as the number of configuration included in the ordered set increased, it became more improbable that any set of weights would order the list exactly as it was arranged by the data processing program. This was accounted for by considering only the first three non-zero digits of the circumferential distortion factor value to be significant. A set of penalty weights which properly ordered this index value rounded to the third digit was considered satisfactory.

A total of 275 different sets of weight values were considered before further progress was considered to require a change in the original distribution of distortion contributions. The final "best" set of component weights is shown in Table VI. The extent of the correlation between configuration and distortion is shown in Figure 33 where each point represents a tested configuration located by its distortion level and total additive configuration penalty weight.

This final set of penalty values was transferred to the initial distortion factor estimate table (Table V), and the adjustment required to bring each row total to the final penalty value was applied to each weight in that row. The relative size of the column totals then reflected the observed importance of the distortion characteristics included in the study. These values comprise the SIGNIFICANCE line of Table VI and represent the final results of this investigation. The effectiveness of this correlational development technique is dependent



Table VI. FINAL PENALTY WEIGHTS

COMP CODE.	ROW TOT.	D	L	%	#	°	UP	DW
B=1	22	0	8.9	0	1.78	11.3	0	0
2	22.5	0	0	0	4.75	17.8	0	0
3	25	0	5.75	4.8	.38	10.8	0	3.25
4	30	0	5.5	13.7	.55	10.3	0	0
5	26	0	6.4	5.3	.43	12.1	0	1.8
C=1,D=3	51	8.1	4.3	0	0	0	0	0
C=2,D=1	51	13.75	15	14.6	1.40	.99	0	4.9
C=2,D=2	34	6.7	8.8	13.8	1.33	.94	0	2.34
C=2,D=4	45	12.3	13.5	13.0	1.25	.88	1.66	2.2
C=3,D=1	47	11.5	12.6	12.2	1.2	1.65	0	4.1
C=3,D=2	45.5	7.7	10.5	19.4	3.1	2.2	0	2.73
C=3,D=4	50	12.4	13.5	15.7	2.5	1.8	1.73	2.2
C=4,D=1	60	13.7	15	21.7	7.4	2.96	0	4.9
C=4,D=2	43	6.6	3.33	20.8	7.1	2.82	0	2.33
C=4,D=5	60	16.7	4.23	26.4	8.9	3.58	0	1.18
C=5,D=2	41.5	6.6	8.8	16.5	2.64	1.87	1.76	3.25
E=1	32	0	4.7	0	0	8	6.25	13.1
2	29	7.75	0	2.06	.41	10.6	8.25	0
3	28	4.1	4.38	4.38	.55	5.6	4.38	4.62
4	25	7.53	3.34	4.68	.53	3.4	2.68	2.82
5	32	12.1	3.23	1.61	.33	8.25	6.46	0
6	33	15.1	1.34	1.34	.27	6.83	5.36	2.82
SIGNIFICANCE FACTOR		162.6	144.9	211.9	46.8	124.6	38.5	58.5



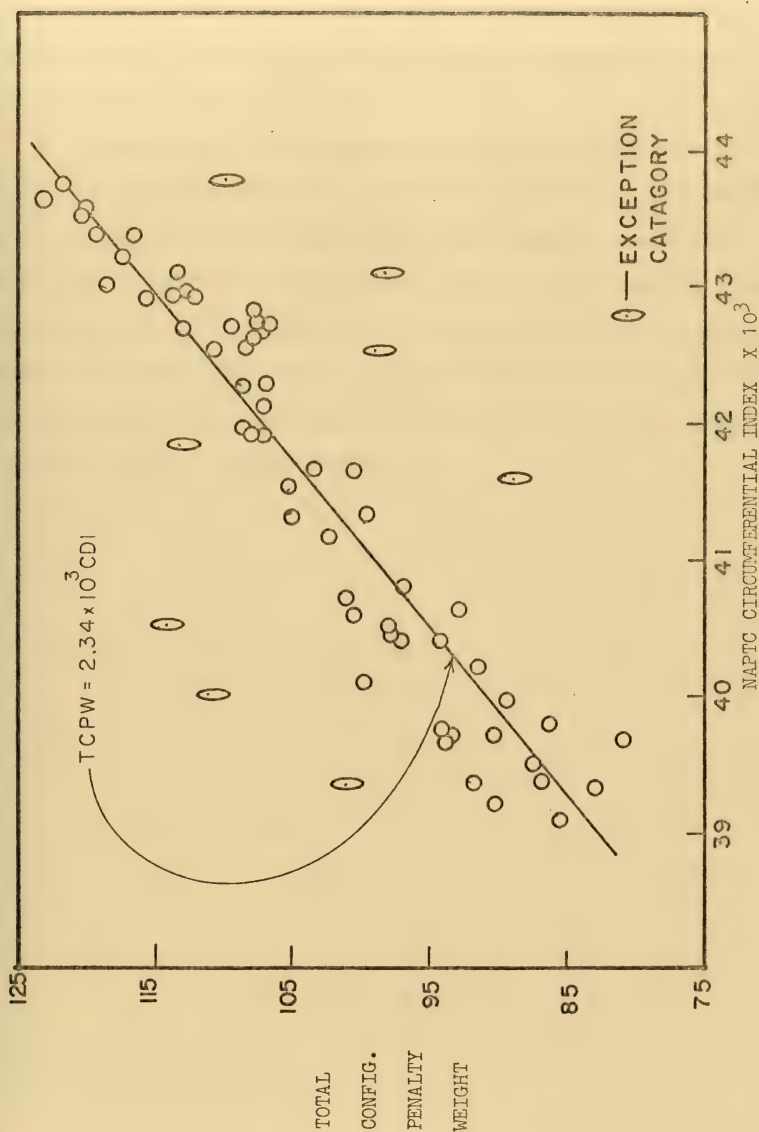


Figure 33. THE CORRELATION OF CONFIGURATION AND DISTORTION





upon the initial selection and distribution of contributing distortion geometry factors. Improvement of correlational accuracy will require iterative alteration of these factors.

Adaptation of this technique to fully automatic machine processing is considered feasible. This is the next step toward development of a fully unified analysis system. This adaptation would make possible the evaluation of refined and expanded sets of component geometry and operating condition factors. Further extension would be necessary to confirm the effect of component sizing properties as well as the shape effects determined here. The steps necessary to execute this expansion are considered in the following chapter.



## VII. GUIDELINES FOR RESEARCH EXTENSION

The experimental techniques, data treatment procedures, and correlational development method validated through this research require extension to establish a fully inclusive empirical theory of large duct aerodynamics. Experimentally it will be necessary to construct additional component models designed to provide variation in size and spacing parameters in the same manner that the components used here differed in basic geometry. The necessity for conversion of the instrumentation to automatic data processing has been discussed and should include in its planning provisions for the reduction of the mean measurement error. The redesign of the power system to permit wider variation and more direct control of primary and secondary flow rates has also been detailed in previous sections.

To fully establish the validity of this experimental analysis method it will also be necessary to observe the effect of varied duct cross section dimensions since many non-square sections are in common use. Similarly it will be necessary to make provisions in future model test sections for the vertical variation of engine position and augmentor location.

In the processing of experimental test data the results obtained in this investigation will have a simplifying effect. Sufficient evidence is available to conclude that the NAPTC circumferential and radial indices are sufficient distortion measures, and the computation of the others described in this report is unnecessary. Additional refinement of the sorting methods used here should provide the capability for sorting on more than one configuration code digit simultaneously. This



would simplify the identification of significant component performances and reduce the number of steps required in the determination of component distortion weights during correlation refinement.

The necessity for automation of the correlation refinement procedure was pointed out in the discussion of the present development. This adaptation should be relatively straightforward as far as duplicating the efforts reported here. Once the optimum set of initial contributions of each distortion factor has been determined, it will be necessary to extend the experimental portion of the investigation to include components of similar geometry and varying dimensions and spacings. This will permit confirmation or adjustment of the relative importance of the included distorting factors for each type of component. The correlation method will then be expanded to account for additional effects including: inlet types other than vertical, engine position in the duct, duct cross section shape, inlet flow rate, and augmentation ratio. Complete correlation will require adequate provision for the EXCEPTION configurations discovered in this project. It will be necessary to predict their unique character and account for their unexpected performance. It is possible that a close examination of these inlets and careful variation of their configuration geometry will greatly assist in the estimation of the significance of geometric characteristics.

It may be desirable to include in future studies additional component designs for inlet covers and acoustic treatments. This will be particularly true if it is found to be feasible to extend this analysis to other applications such as the inlet ducting for shipboard gas turbine power plants [Ref. 45]. Completion of the development to this



point will constitute one half of the total effort as it will still be necessary to account for dynamic distortion effects.

If the conversion of the instrumentation includes the addition of low response time total pressure transducers in the survey rake, dynamic data may be acquired simultaneously with that required for the above refinements. NAPTC has developed dynamic distortion indices similar to those employed in this development, and it is to be expected that a parallel test program will produce a correlation between inlet configuration and dynamic distortion levels.

Finally, it will be necessary to present the complete research results in easily applied handbook form for distribution. This phase is of paramount importance; and until it is successfully accomplished, the research, however complete, will have failed to meet its ultimate goal and justify its costs.





## VIII. CONCLUSIONS

Based on the results of this investigation, it can be concluded that testing of three dimensional flow models is a viable method for the analysis of test cell inlet flow. It appears that relatively unsophisticated experimental methods and standard, widely available, data reduction techniques can, with sufficient effort, produce substantial improvements in future test cell designs. Pending completion of correlational development and comparison with full testing of actual cells, it is reasonable to expect that experimentally determined configuration-to-distortion correlations will accurately predict cell distortion performance. Completion of the research initiated in this project will provide the means to determine optimum inlet configurations for test facilities with known operational requirements.

No attempt was made to evaluate the effectiveness of the distortion indices in predicting engine performance, but no correlation with configuration was possible with any distortion index other than those furnished by the Naval Air Propulsion Test Center. Currently available handbook methods for the prediction of total pressure losses in ducted flows were found to be adequate for use with test cell inlet models.

The data collected in the course of this investigation may be utilized in the prediction of cell performance for configurations having components similar to those described in this report. These configurations are listed in the Computer Output section. To utilize these results, consult Table II and determine the coded designation of the configuration which is of interest; locate this code number in the numerically ordered data summary and note the indicated value of the



circumferential distortion index. This value will permit rapid location of the configuration code in the table which is ordered according to distortion level. The position of the configuration code in this list will permit initial estimation of inlet performance. Those located in the upper or lower third of this ranking will provide satisfactory and unsatisfactory performance, respectively. For those configurations having indices which place them near the middle of this list, it is necessary to identify the range of compressor rpms which will be tested and compare it with those assumed in the determination of satisfactory performance.

This investigation was the first step in a lengthy development. It provides the basis for continuation of this development, and the results support the contention that complete success is possible with sufficient support.



# APPENDIX A

## COMPUTATION OF THE MODEL LENGTH SCALE FACTOR

The similarity condition for the model is that

$$\frac{B V_m^{-2} X_m^{.8}}{L_m} - \frac{B^2 V_m^{-4} X_m^{1.6}}{L_m^2} = \frac{B V_c^{-2} X_c^{.8}}{L_c} - \frac{B^2 V_c^{-4} X_c^{1.6}}{L_c^2}$$

For this investigation:

$$L_m = 1.0 \text{ feet}$$

$$L_c = 24.0 \text{ feet}$$

$$B = 0.1741 \text{ ft}^2/\text{sec}$$

$$V_c = 40.0 \text{ ft/sec}$$

Evaluating this condition in an iterative manner, treat  $x_c$  as a constant and define

$$C \equiv \frac{B V_c^{-2} X_c^{.8}}{L_c} - \frac{B^2 V_c^{-4} X_c^{1.6}}{L_c^2}$$

and

$$Y \equiv \frac{V_m^{-2} X_m^{.8}}{L_m}$$

With these, the similarity requirement becomes

$$B Y - B^2 Y^2 = C$$

or

$$B^2 Y^2 - B Y + C = 0$$

Then, taking

$$E = \frac{C}{B}$$



this becomes

$$B y^2 - y + E = 0$$

Applying the quadratic formula,

$$y = \frac{1 \pm \sqrt{1 - 4EB}}{2B}$$

For a selected value of  $x_c$ , the value of  $x_m$  is then available from

$$x_m^{.8} = y L_m / V_m^{-0.2}$$

or

$$x_m = y^{1.25} L_m^{1.25} V_m^{0.25}$$

The model length ratio is thus:

$$\frac{x_m}{x_c} = \frac{y^{1.25} V_m^{0.25}}{x_c}$$

In a similar manner, the variation in simulated cell velocity with changes in model flow rate may be determined with

$$C \equiv \frac{B V_m^{-.2} x_m^{.8}}{L_m} - \frac{B^2 V_m^{-.4} x_m^{1.6}}{L_m^2}$$

$$y \equiv \frac{V_c^{-.2} x_c^{.8}}{L_c}$$

so

$$C = B y - B^2 y^2$$

$$E = \frac{C}{B}$$

and

$$B y^2 - y^2 + E = 0$$





As before

$$\gamma = \frac{1 \pm \sqrt{1.0 - 4BE}}{2B}$$

This relation is then evaluated at selected combinations of  $V_m$  and model length ratio. From these  $\gamma$  values, the effective cell velocity is then available

$$V_c^{-.2} = 24.0 \gamma X_c^{-.8}$$

or

$$V_c = (24 \gamma)^{-5} X_c^4$$

where

$$X_c = \frac{X_m}{\text{Model Length Ratio}} .$$



## APPENDIX B

### ESTIMATION OF EXPERIMENTAL ERROR

The experimental measurements in this investigation were subject to three kinds of errors: systematic errors, mistakes, and random errors. Systematic errors were reduced by careful debugging of the instrumentation system and data reduction techniques. The procedures followed in this investigation were initially designed and continuously revised in an effort to minimize these errors. The results of final comparisons and standardization checks confirmed the virtual absence of systematic errors, and these are neglected. Errors due to mistakes were minimized by the length of the experimental program which permitted the accumulation of considerable experience. Early operation revealed several common mistakes in both data acquisition and processing techniques. Checks were then incorporated to guard against their repetition. The data processing programs were developed with intrinsic error checks and for rapid reprocessing of accumulated data when errors were detected.

Random errors were mainly due to random behavior of the system and the inherent inaccuracy of the instrumentation. The magnitude of these errors may be estimated in the following manner:

The velocity vectors were calculated from the equation,

$$V = \sqrt{\frac{2(P_o - P_s)g_c}{\rho}}$$



where,

$V$  = Magnitude of the total velocity vector, ft/sec

$P_o$  = Total pressure, lbf/ft<sup>2</sup>

$P_s$  = Static pressure, lbf/ft<sup>2</sup>

$g_c$  = Proportionality factor, 32.17  $\frac{\text{lbm-ft}}{\text{lbf-sec}^2}$

$\rho$  = Local density, lbm/ft<sup>3</sup>

The local density,  $\rho$ , was computed from the perfect gas law equation

$$\rho = P_s / R T_s$$

where

$P_s$  = Local static pressure (absolute), lbf/ft<sup>2</sup>

$R$  = Gas constant for air, 53.34 ft-lbf/lbm-F

$T_s$  = Static temperature, deg. Rankine

In terms of the measured quantities, this is

$$V = \sqrt{\frac{334.42 (h_s - h_o) SG}{\rho}}$$

where

$h_s$  = Measured manometer deflection for static pressure, inches

$h_o$  = Measured manometer deflection for total pressure, inches

$SG$  = Specific gravity of the manometer fluid

The logarithmic differential of this equation is

$$\frac{\Delta V}{V} = \frac{1}{2} \left( \frac{\Delta(\Delta h)}{\Delta h} + \frac{\Delta \rho}{\rho} \right)$$



assuming that the error in the specific gravity is negligible. The error in density is

$$\frac{\Delta \rho}{\rho} = \frac{\Delta P_s}{P_s} + \frac{\Delta T_s}{T_s} .$$

Assuming the maximum variation in the absolute static pressure and the static temperature to be 0.05 in Hg and 2°, the maximum error in the density is

$$\frac{\Delta \rho}{\rho} \times 100 = \left( \frac{0.05}{29} + \frac{2}{530} \right) \times 100 = .17 + .38 = 0.6\%$$

For a manometer deflection of 2.5 inches, the observed reading error was about 0.2 inches. The error in the total velocity is therefore

$$\frac{\Delta V}{V} \times 100 = \frac{1}{2} \left( \frac{0.2}{2.5} + .006 \right) \times 100 = 4.3\%$$

For several sample data sets the recorded data was adjusted by this amount and then reprocessed with the result that a variation of 0.00006 to 0.00012 was produced in the circumferential distortion factor. This 0.15 to 0.3 per cent error in the magnitude of the distortion factor corresponds, for the collected data of this investigation, to from three to eleven positions in the distortion order ranking.





## APPENDIX C

Pages 120 through 200 constitute Appendix C and are a reprint of NPS-57Ba, To72061A which was written after the completion of the background research which established the aims of this investigation. Reference and Figure numbers apply to the listings which appear within the appendix. To simplify the use of page number references in this reprint the original page numbers appear in parenthesis.



# NAVAL POSTGRADUATE SCHOOL

## Monterey, California



PRODUCTION TEST FACILITIES FOR TURBOJET  
AND  
TURBOFAN ENGINES - 1975 to 1995

D. L. Bailey LT, USN

P. W. Tower LT, USN

May 1972

Approved for public release; distribution unlimited.



NAVAL POSTGRADUATE SCHOOL

Monterey, California

Rear Admiral A.S. Goodfellow, Jr., USN  
Superintendent

Milton U. Clauser  
Provost

ABSTRACT:

A review is made of test cell design options in order to identify characteristics of jet engine test facilities to be constructed in the 1970's and designed to be operable for a minimum of twenty years. The necessity of providing replacements for many current facilities is documented, and the factors which will ensure future production capability and economic feasibility are detailed. Present turbine engines are reviewed and projections of future engines and aircraft are made. A confidential supplement is included for qualified receivers.

Experimental investigations of inlet flow patterns and engine exhaust-augmenter relationships are being carried out. Results will be published in thesis form in October 1972, by the Naval Postgraduate School, Monterey, California.



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## I. INTRODUCTION

Through the 1960's satisfactory engine test facilities consisted of large rainproof buildings located and constructed in such a manner that the nearest neighbors were not permanently deafened. Today, the evolution of aircraft propulsion systems has rendered some of these installations unuseable long before their physical deterioration would have done so. Turbojet test cells constructed during the next decade will be required to meet a greatly expanded and refined definition of satisfactory performance. Factors such as increased thrust, use of high bypass turbofans, proliferation of special-purpose turbine engines, inflation of real estate and utility costs coupled with reduced availability and the recognition of the need for environmental protection will increase the cost and the challenge of designing test facilities operable through the 1990's.

It is the purpose of this report to identify the essential characteristics of the jet engine test facilities to be constructed during the 1970's and to provide a summary of the techniques available to meet these requirements. In the following sections the necessity of providing replacements for current facilities is documented, and the factors which will ensure future production capability and economic feasibility are detailed.





## II. ENGINES

### A. PRESENT

Aviation Week and Space Technology magazine, in its annual inventory issue, presents a comprehensive summary of the types and sizes of aircraft propulsion systems in use with operational aircraft. The largest in each class is of primary interest to the test cell designer but account must be taken of the wide variation within classes. Within the class of turbojet engines, thrust varies from 30,000 pounds (J58 in the SR 71) to 170 (WR24-7 in drones) and the corresponding lengths vary from 22 to 2 feet.

The facility designed to service turboshaft engines would have to handle variations in shaft horsepower from 5000 SHP (J56-A-15) to 300 SHP (TSE 36) as well as length and weight changes. Similarly, turbofan engines in military use come in one to nine-foot diameters (Harpoon and C5) and have weights of 100 to 7500 pounds. Review of current engine useage makes it obvious that the facility mission must be carefully established prior to initiation of design.

### B. FUTURE

In the past, varied aircraft types were powered by similar engines. New technology developments have changed matters dramatically, as evidenced by the present differences between



characteristics of high bypass turbofans and afterburning turbojets. Future changes and developments will require more precise matching of engines and airframes for specific missions [Refs. 1, and 2].

The Navy of the future will move strongly towards utilization of gas turbine powered surface vessels. These may be surface effect vehicles (SEV), or standard design vessels, but their propulsion systems will need overhaul and repair facilities similar to those of a Naval Air Rework Facility (NARF).

Because of the vast differences of engine types, it may not prove feasible to build a single test cell capable of testing all engines. Present Navy policy is to assign the overhaul and repair responsibility of a particular type engine to each NARF. The purpose of this section is to correlate engine characteristics and projected aircraft performance.

The first advanced technology engines for Navy fighter aircraft will be used in the F-14 Tomcat. Early versions will utilize the Pratt and Whitney TF-30 412 engine, and F-14B models will be equipped with the more powerful F401 PW 400 engines. The latter engine is in the 20-30,000 pound thrust class and will have an air flow rate at full power of about 300 pounds per second. If an augmentation ratio of 2:1 is chosen a test cell flow rate on the order of 900 pounds per second will result. Other engine manufacturers are also developing afterburner equipped engines in the 25,000 pound thrust category [Ref. 3].

Further fighter aircraft developments will bring to the Navy the ADLI, or Advanced Deck Launched Interceptor. The ADLI will utilize



an advanced technology engine with turbine inlet temperatures in excess of 3,000° F. Also, advanced hybrid multicycle engines are being developed and will be introduced to operational use during the life of test cells built in the present decade [Ref. 4]. Turboramjets or supercharged ejector ramjets (SERJ) are also being developed. Discussion of these engines are contained in the confidential supplement to this publication.

Future attack aircraft must combine the capability of high subsonic cruise speeds with the ability to loiter for long periods over target areas. Non-afterburning turbofan engines are presently in use and their continued development and refinement is predicted.

The U.S. Marine Corps presently have the Harrier (AV-8A) in operational use. The Navy may move toward procurement of Harrier aircraft in the near future and advanced vectored thrust V/STOL aircraft within the next ten or fifteen years. The Harrier utilizes the Pegasus turbofan engine with variable nozzles which is built by Rolls Royce. The advanced Pegasus 15 will have 25,000 pounds thrust and an airflow requirement of 450 pounds per second. A requirement for testing these engines is that shrouds and ducts be installed for directing the exhaust streams of the individual nozzles into a common exhaustor [Ref. 5]. Total cell requirements for this engine will also be 900 pounds per second with a 1:1 augmentation ratio.

The Navy is currently developing the S-3 carrier based ASW aircraft, which is powered by the General Electric TF-34 turbofan



engine. This is a 9,000 pound thrust engine with an airflow capacity of about 300 pounds per second, and will be the first engine that the Navy operates that will be tested in the same configuration as it is mounted on the aircraft. That is, it will be pylon mounted, thereby requiring an overhead thrust bed. Because of the large mass flow through the turbofan engine any pressure variations in the cell acting across the fan exhaust will cause errors in thrust measurement. The TF-34 has a bypass ratio greater than 6:1. Because of the exhaust characteristics of turbofan engines care must be taken in matching the engine and augmentor to avoid excess air entrainment over that which is required for cooling purposes, thereby increasing the cell depression [Ref. 6].

Future patrol aircraft developed to be introduced in the 1980's may utilize large fan engines. Other aircraft using the same type engines may be those developed to replace the Navy's present transport fleet. Military transports with STOL capability will require turbofans in the 25-30,000 pound thrust category [Ref. 7]. The airflow through an engine of this size will be on the order of 1,000 pounds per second and total cell airflow could run as high as 2,000 pounds per second, depending on the augmentor design.

Smaller logistic aircraft, successors to the C-2 COD aircraft, may use turbofans in the 5-10,000 pound thrust class. These will be similar to the above-mentioned TF-34 in flow requirements, and test facility requirements will be similar as well.





Future weapons system acquisition will have a bearing on aircraft design, and therefore on engine design. Work is presently being done to develop laser weapons for aircraft use. For some missions, the effectiveness of this weapon is proportional to the power which can be generated in the transporting aircraft and such systems may require a platform as large as the Lockheed C-5A [Ref. 8]. If the Navy were to acquire such a system for strategic defense, it would find itself in possession of turbofan engines in the 50,000 pound thrust category, having airflow requirements of 1,500 pounds per second and requiring a test facility capable of handling 3,000 pounds per second airflows.

Consideration also must be given to the testing of turboshaft engines used in large rotary-wing aircraft. Facilities must be available for the measurement and absorption of the shaft energy generated by such engines. Similarly, turbine engines used for surface ship propulsion systems will require complex gearing and energy absorbing systems [Refs. 9 and 10].

Other trends in engine/airframe mating techniques will require some modification of test cell design and operation. The F-14 aircraft will utilize non-interchangeable left hand and right hand engines. This may mean that reversible mountings, slave accessories and so forth will be required in cells.

In order to minimize drag associated with nozzle and airframe interaction, non-axisymmetric nozzles may be employed in the future.



This possibility implies a requirement for an augmenter tube designed to permit replacement of the receptor bellmouth.

Knowledge of systems on the horizon which may eventually become operational is essential to provide flexibility and long life for projected test facilities. Prior to test cell design initiation, the update of each subject must be accomplished.



### III. SUMMARY OF TEST FACILITY REQUIREMENTS

Figure 1 is the most accurate summary of test cell requirements available from current sources. As with any forecast, it includes some uncertainty; but the information included is as authoritative as possible, having been collected from engine manufacturers, Department of Defense planning agencies, published reports of service sponsored research, and interviews with facilities planners for several test cell operators. These data makes it clear that the decision as to facility capacity will restrict usage plans for extended periods and that the operator will require guidance by policy level managers to determine final construction requirements.

Gerend [Ref. 11] provides a simple method of predicting turbine engine weights and dimensions. This method has been used to check the credibility of this summary information. These projections are specifically confined to facilities for sea-level testing only. Forecasts of requirements for altitude test facilities are available in Refs. 12 and 13.



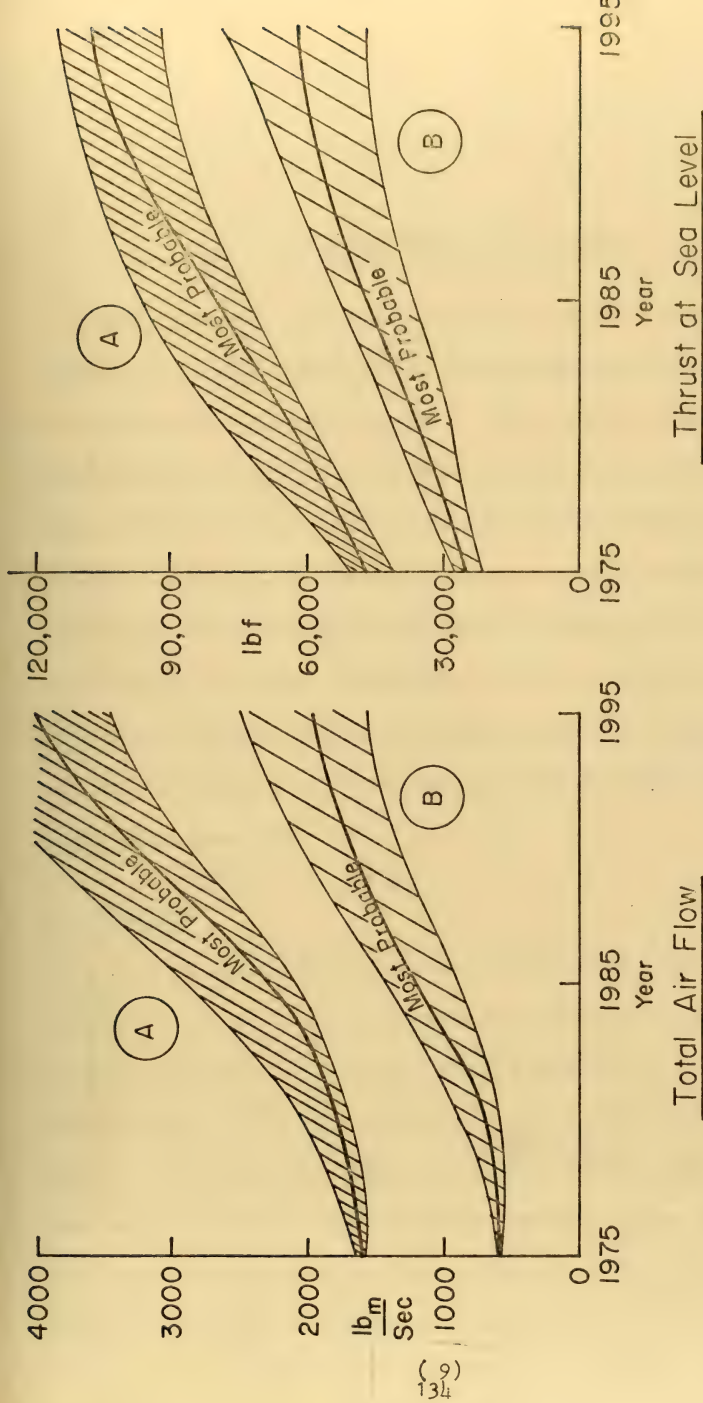


Figure 1.





#### IV. PRESENT TEST CELL DESIGNS

Many currently operational jet engine test cells, both in the military and civilian communities, were designed and built to test the early generations of turbojet engines. These may be defined as the state of the art engines of the 1950's. In other instances, some even older test cells are in existence. The Naval Air Rework Facility at NAS North Island, California has several operational cells which were initially built to test reciprocating aircraft engines. These are still in use testing J-57 and J-79 engines, but their performance is marginal now and will be aerodynamically and environmentally unsatisfactory for the engines which will reach operational status in the next twenty years [Ref. 14].

##### A. INLETS

Many of the oldest test cells were engineered so as to take maximum advantage of existing construction and to minimize costs. This practice is illustrated in Figure 2 which schematically illustrates the characteristics of the two oldest turbojet test facilities at NAS North Island. Of primary interest is the design of the inlet and the lack of consideration given to requirements for uniform airflow into the engine. The large block shown in the plenum chamber was the original test stand for the testing of reciprocating engines.



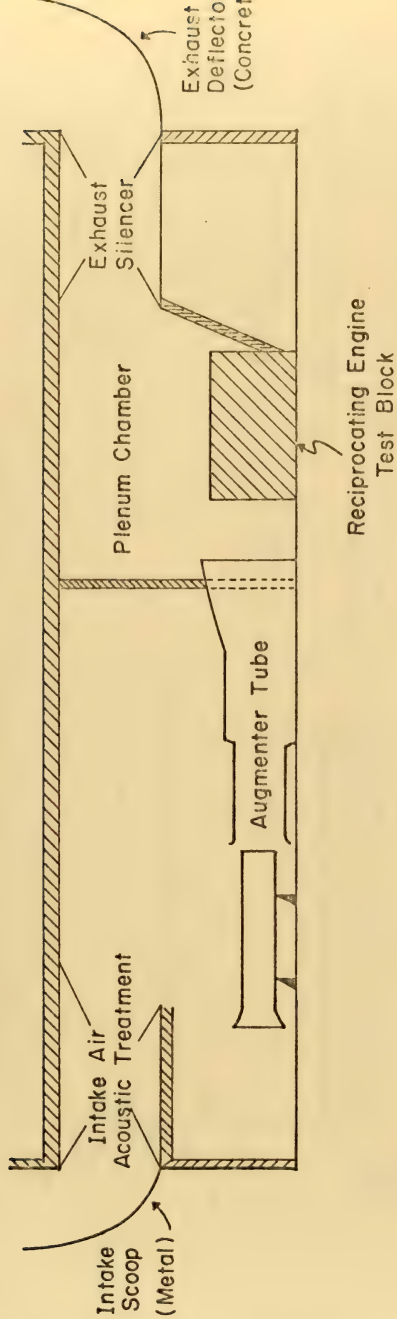
The next generation of test cells was designed with some added sophistication. It was realized that the test section itself should be long enough to provide for some flow straightening forward of the engine bellmouth. Such cells are typified by the installation shown in Figure 3 which depicts the general design of NARF North Island's depot level test cells designed and built in the late 1950's.

The cell aerodynamics are obviously cleaner than those previously shown, and in operational use with present afterburner equipped engines they have been satisfactory. In all such installations certain compromises are made between the desired operational characteristics and economic constraints.

Modern turbine engines, particularly turbofan engines, have proven highly sensitive to aerodynamic distortion in poorly designed test cells. Large engines such as the General Electric CF6 and the Pratt & Whitney JT9D are built without inlet guide vanes, and, as a result, any distortion in the inlet flow field can have an effect on engine operation. General Electric considers total pressure distortion greater than two inches of water above or below the mean measured at the fan or compressor face unacceptable, and endeavors to reduce this difference to less than one inch  $H_2O$  [Ref. 15].

Modern test facilities built to test these large fan engines, as well as any future engines, have been designed to reduce inlet distortion as much as possible. United Air Lines' overhaul facility in San Francisco exhibits one of the simplest inlet designs. Air enters through





Test Cells 13, 14 Nas North Island.  
Figure 2.



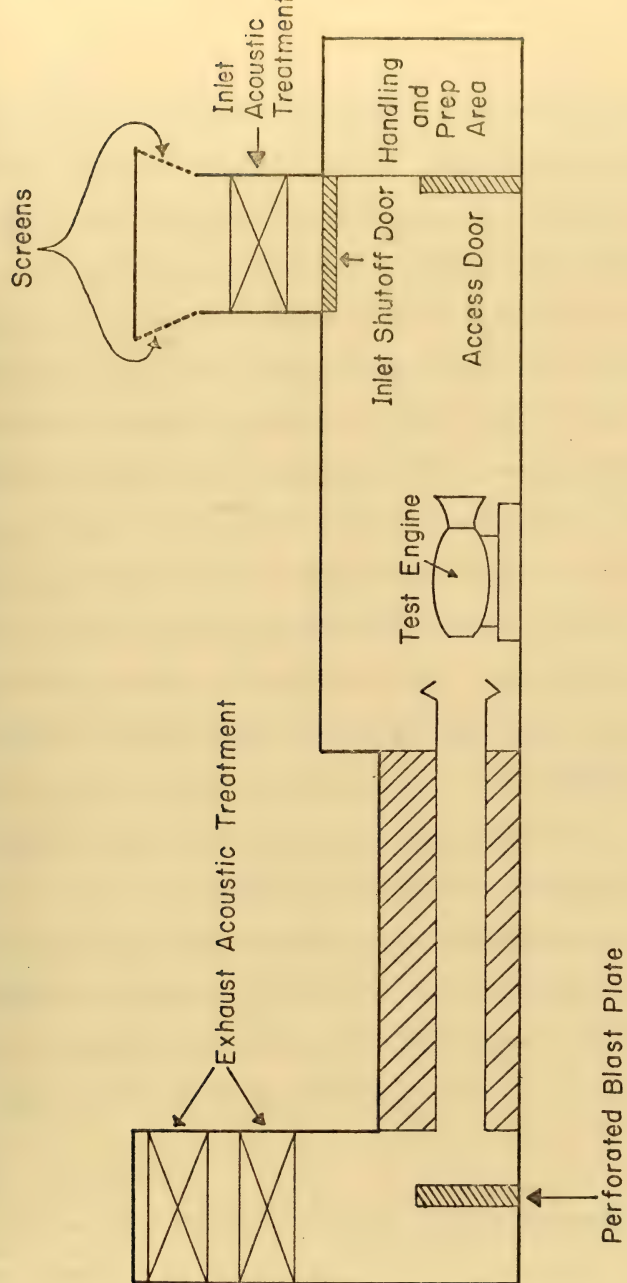


Figure 3. Test Cells 19 and 20, Nas North Island.





the horizontal inlet, passes the acoustic treatment and enters the test section without encountering any turns. This design is obviously easier to construct than one having a large vertical inlet.

A second example of modern design philosophy is exhibited in the test cell operated by Pacific Airmotive Corporation in Burbank, California. The vertical inlet is flush with the roof structure; turning vanes are installed to minimize the losses caused by the 90° turn. Turning vanes or flow straighteners will become increasingly necessary as test cell airflow design limits are approached. Some modern cells are designed so that turning vanes may be added in the future. The installation operated by AiResearch Manufacturing Co., in Torrance, California, has a vertical inlet. The only present requirement for flow treatment is a corner fairing to reduce separation at the inlet bend, but designs have been drawn up for the addition of turning vanes when future requirements so dictate [Ref. 16].

A prime consideration in the use of flow treatment is the method of installing the engine in the test cell. The simplest and cheapest method of construction is to build a front-loading cell. However, if flow treatments are installed, this design requires that they be movable or that a portion of the treatment be hinged.

## B. EXHAUSTS

The basic philosophy of present exhaust treatments is to remove the majority of the kinetic energy from the jet exhaust, to cool the exhaust by mixing with secondary air or water, and to lower the noise



level of the exhaust. Removing the kinetic energy is also a method of acoustic treatment. The most common method of accomplishing the first two objectives is to utilize the kinetic energy of the exhaust to pump secondary air through the cell and into the exhaustor or augmentor tube where mixing of the two streams occurs. Augmentation ratio, defined as the ratio of secondary air mass flow to engine air mass flow, is an important consideration in determining overall cell design. With an excessive augmentation ratio the depression limits of the cell may be exceeded; with too small a ratio, desired cooling may not be accomplished, and temperature limits of test cell exhaust components such as installed acoustic treatment may be exceeded. Present design goals for augmentation ratios are 2:1 for turbojet engines and 0.25:1 to 0.5:1 for high bypass turbofan engines [Refs. 5, 12, and 15]. Some facilities, however, still have augmentation ratios as large or greater than 1:1 for large turbofan engines [Ref. 17]. Turbulent mixing phenomena are not well understood, and much work remains to be done in analyzing the ejector system.

Water cooling is usually required for an engine operating in afterburner; the augmentation ratio required to cool the exhaust without water is greater than 6:1. The minimum amount of water usage is desirable in order that water supplies be preserved. Many cells utilize spray rings mounted inside the augmentor. These operate very inefficiently because of the difficulty of penetrating the hot, high speed core of the exhaust [Ref. 18]. Several attempts have been made to



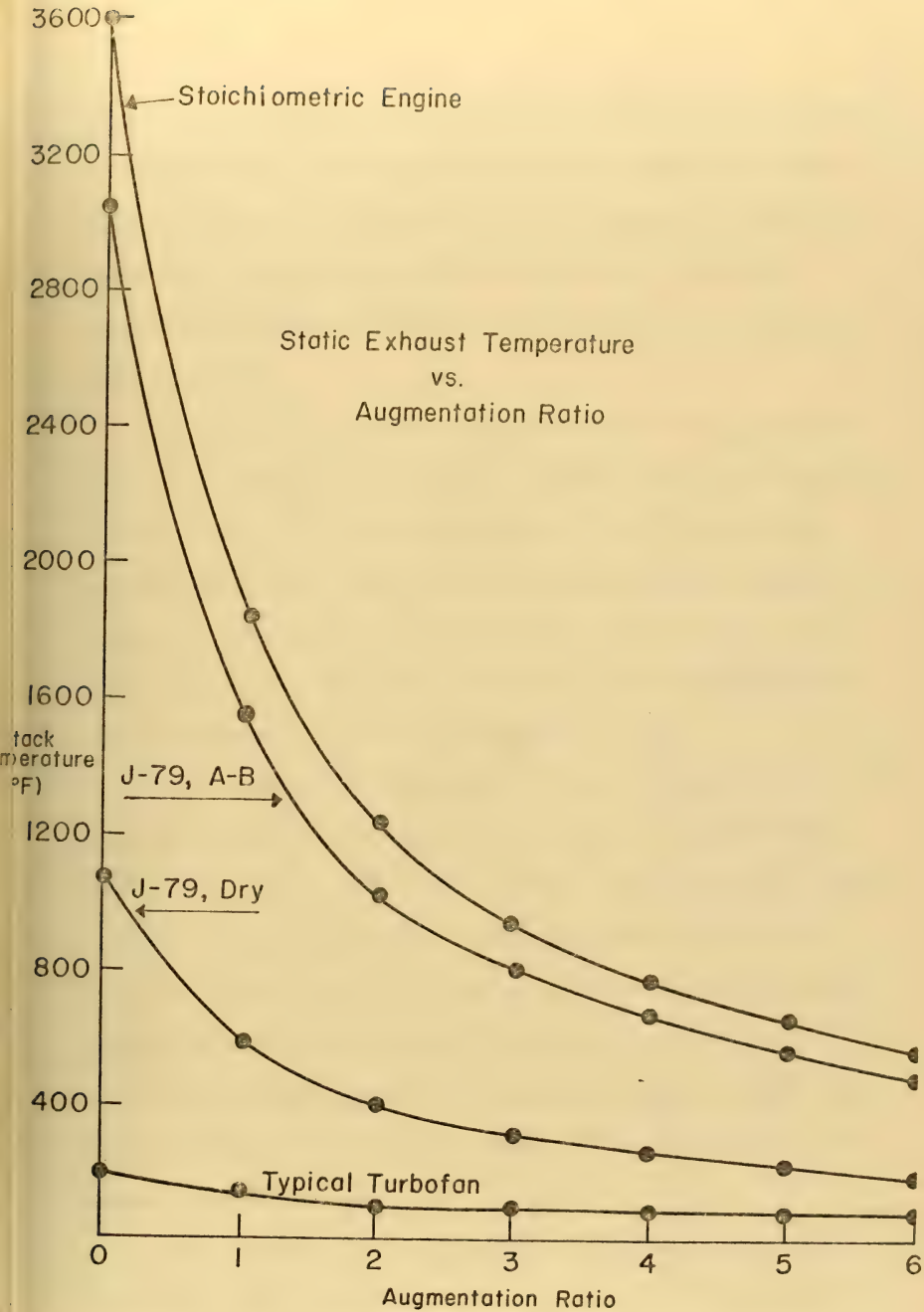


Figure 4.



inject the water from within the core itself. The water sparger [Ref. 19] is an example. Care must be taken in the design of such items, since they can produce undesirable acoustic phenomena if their natural frequencies correspond to the driving frequencies of the exhaust. Further development of water injection is a necessity for economical future operation.

One method available for removing the kinetic energy of the jet exhaust is the "brute force" method. At NARF North Island in cells 13 and 14 [Fig. 2], the exhaust impinges on a solid concrete block, lined with steel plate. This is effective in destroying the continuity of the stream, but has failed to prevent serious damage to the walls of the plenum chamber [Ref. 14]. In the newer cells at North Island the exhaust impinges on a perforated steel plate [Fig. 3].

A newer method of treating the flow, one coming into more general use [Refs. 16, 17, 20, and 21], involves a colander in the form of a cylinder or a cone. The colander is the last section of the ejector tube, and is perforated with holes, usually on the order of 1-1/4" in diameter [Ref. 15]. This serves to break up the flow and changes the low frequency noise of the exhaust into more easily attenuated higher frequencies. Work remaining in this area involves the study of placement and sizing of the holes so that uniform flow in the exhaust stack is attained.

Other methods of exhaust treatment will become necessary in the future. Environmental protection standards will require pollution





abatement systems for engine test facilities. These systems will require close matching between the engine nozzle and the exhauster, because any excess mass flow will unnecessarily load the abatement equipment. Also, in some cases, the flow needs to be properly conditioned before it reaches the abatement system [Ref. 22].

### C. GENERAL

Because of the relatively small flow rates, older turbojet engines could be tested in close proximity to cell boundaries. The larger engines now coming into use must be tested with adequate clearance from floors, walls and ceilings to reduce velocity distortions. This clearance can only adequately be provided by overhead thrust bed systems. Because thrust measuring devices above the engine are subject to conductive heat transfer they must either be monitored for temperature changes or kept at a constant temperature. United Air Lines' facility in San Francisco has both such systems installed [Ref. 17]. Current thrust measurement accuracy is typically  $\pm 56$  lbs. for an engine thrust of 41,100 lb. [Ref. 23].

Overhead mounting systems have introduced a new problem to test operations in that the height of the engine when mounted in the cell makes accessibility difficult. United Air Lines has installed a hydraulically lifted platform beneath the mounting system. During actual testing the platform is lowered to a position flush with the floor, providing smooth passage for the secondary air past the engine [Ref. 17]. Another solution to this problem was developed for the previously



mentioned AiResearch facility [Ref. 16]. The work platforms are suspended from the overhead at a convenient height, and are swung up and locked next to the ceiling during engine operation.

In many older cells considerable time is used in preparing and mounting the engine for test. If this time is kept to a minimum, total cell running time can be maximized. Modern design philosophy reduces the man-in-cell time by allowing much of the preparatory work to be done in the handling area rather than in the cell itself. In the handling area the engine is fitted to a specially designed adapter. Necessary engine connections for starting air, fuel, instrumentation leads, and external power are made to the adapter. The entire assembly is then moved to the cell area, and is hoisted to the thrust bed by a winch assembly in the thrust bed itself [Refs. 16, 17, and 20].

Means of handling and transporting the engine are also varied. Many facilities use wheeled dollies for transporting the engine and related assemblies [Refs. 16 and 17]. Some newer facilities utilize overhead monorail systems both in the handling and preparation areas and in the cell itself [Refs. 19 and 24]. Some problems have developed with monorail systems, however, and complete flow analysis must be accomplished before utilizing such a handling system. In one situation [Ref. 19], it has been found that vortices are formed by flow interaction with the monorail, causing serious flow distortion in a cell designed to test large turbofan engines.

Recently, attempts have been made to improve operator visual



contact with the interior of the cell. The usual method of providing this contact is to provide a window between the control room and the cell. Whenever the cell structure is penetrated, additional acoustic problems are created; in order to provide minimum noise levels within the control room there should be no direct connection between the cell and the control room. One alternative to windows has been to install closed circuit television. NARF North Island has installed three black and white cameras in their large cells. These cameras have no zoom or pan capability, and have not met with complete operator approval. Also, they do not obviate the need for entrance into the cell by technicians to check for fuel or oil leaks when the engine is operating.

Because of the varied engines which must be tested in one cell, consideration must be given to the ease with which cell hardware can be adjusted for various engine sizes. NARF North Island utilizes the movable augments concept. The United Air Lines facility uses a jackscrew arrangement to adjust the thrust bed position. The range of adjustment will depend on the size of engines projected to be tested and the means of providing adjustment is up to the option of the designer.

Modern test facilities are being equipped with automatic data acquisition and processing capability. AiResearch Manufacturing Co. has an excellent example of a system designed for developmental engine testing and United Air Lines possesses a system designed for production testing of overhauled and repaired engines [Refs. 16 and 17].



Most of the above information is applicable to depot level test cells for large overhaul facilities. Other proposals have been made for developing smaller test cells for use in intermediate level maintenance facilities. The Ground Support Equipment division of the Naval Air Engineering Center, Philadelphia, Pa., has designed the cell shown in Figure 5. This design differs greatly from those discussed in this section. A primary difference is the construction technique utilized. The cell shown is constructed from pre-fabricated sections and is designed to be demountable if the need should arise. The flow design is different in that separate intakes are provided for the primary (engine) and secondary (augmentation) airflows. Complete aerodynamic analysis is required for this and other major design alternatives.

A listing of some persons and firms conversant with current test cell design philosophy is given in Appendix B.





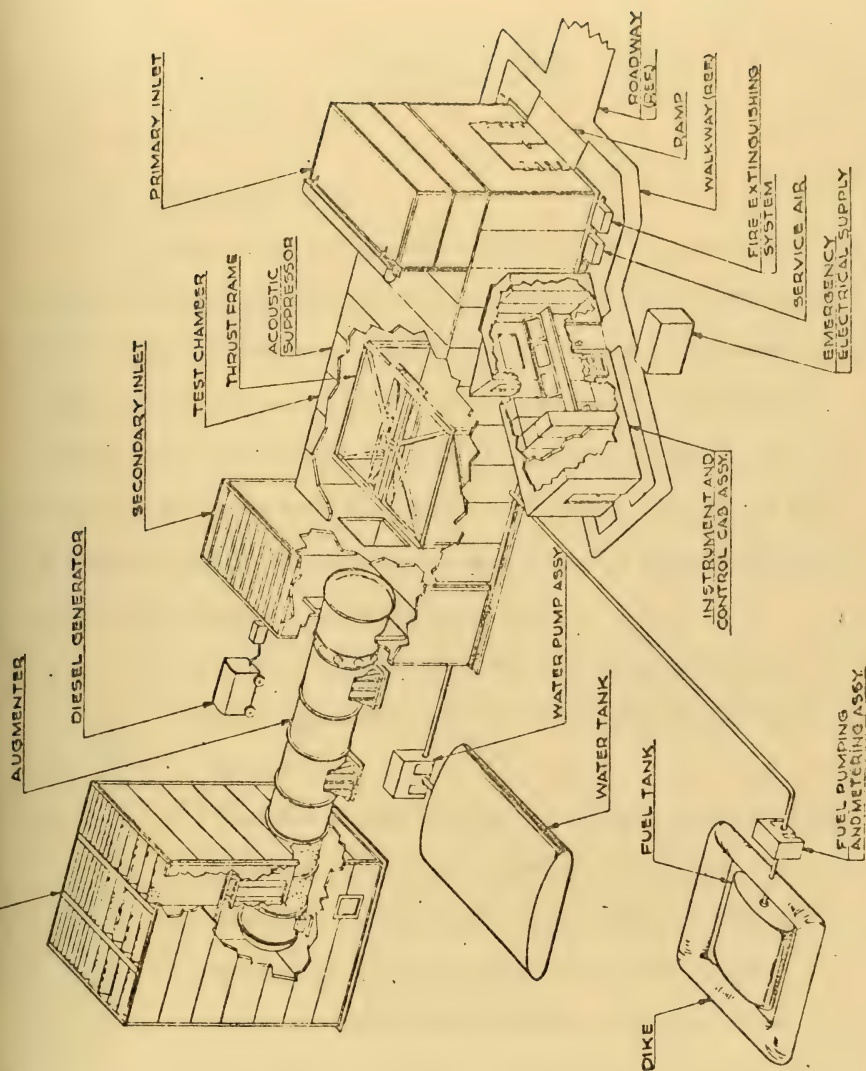


Figure 5. Demountable Test Cell.



## V. DESIGN OPTIONS

### A. INLET

#### 1. Acoustic Control

The current development of commercial STOL aircraft and increasingly stringent airport noise level restrictions [Ref. 25], have resulted in extensive on-going research directed at reduction of engine generated acoustic power. It is reasonable to expect that the engines now in service will be the noisiest, per pound thrust, with which new test cells must cope [See Fig. 6], [Refs. 26, 27, and 28]. It is equally certain that new test cells will require some form of inlet acoustic treatment for the following reasons:

- a. Current, noisy engines will still be in service after the anticipated introduction of the replacement cells [Ref. 28].
- b. Turbofan engines increase the acoustic power directed upstream into the inlet [Refs. 27, 29, and 30].
- c. Military aircraft will continue as the least restricted in required acoustic abatement by virtue of their mission and environment [Refs. 31, 32, and 33].
- d. The test cell structure alone will not be able to absorb the acoustic power produced by even the quietest of



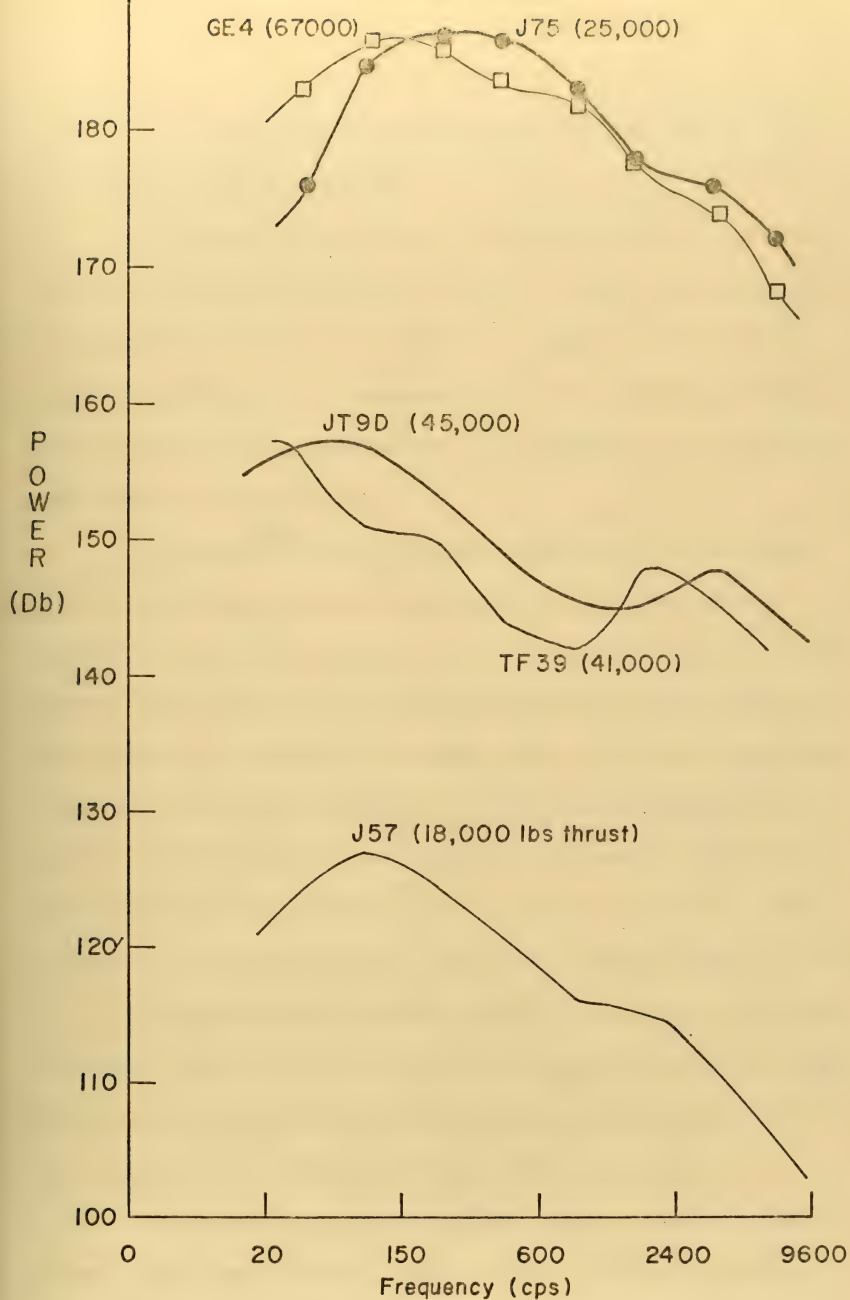


Figure 6. The effect of engine type and thrust on sound power levels.



projected future engines [Refs. 12, 25, 26, 27, 28, 31, 32, and 33].

Accepting the necessity of including specific acoustic treatment several options are available [Fig. 7]. Many of the designs for which performance data are available are proprietary ones and the cost of acquisition must be weighted against that of locally produced designs which must be oversized to compensate for the less complete information on effectiveness.

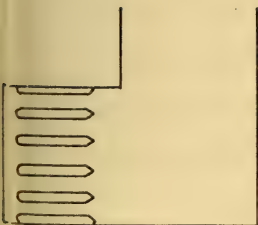
Flat baffles are the simplest of the duct obstruction types. Of sheet metal and fiberglass composition they can, with careful streamlining, provide acceptably low levels of flow distortion. Adjustment of length, thickness and spacing can match acoustic absorption characteristics to specified frequency ranges. The overall flow length required to meet both acoustic and aerodynamic limits may be the greatest for this option and the increased cell length or stack height must be off-set by simplicity of installation and replacement. Both proprietary and non-proprietary designs are available [Refs. 12 and 28].

Staggered baffles require less total flow length for the same absorption and produce less aerodynamic distortion than the flat types. They are also more difficult to construct and replace though reduced total size may ease handling difficulties [Refs. 28 and 34].

The sinuous passage treatment requires a length and produces a distortion level intermediate to those of the two baffle types. Construction and installation is more difficult and expensive than







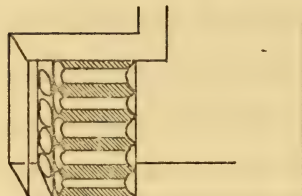
1 Flat Baffle



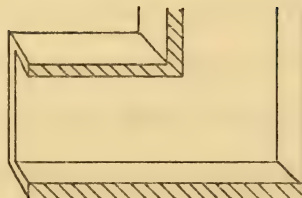
2 Staggered Baffle



3 Sinuous Passage



4 Tubular



5 Lined Walls

1-4 may be used  
with Horizontal  
Inlets.

Figure 7. Inlet Acoustic Treatment Options.



either of the baffles, but proprietary designs are available which permits single panel replacement [Refs. 28 and 33].

The acoustic performance of the tubular treatment reduces the total flow length required below that of the other options but the distortion level in some operating conditions may demand an increase in mixing length which offsets this gain. Additionally they may prove incompatible With good turning vane performance when used in a vertical inlet. The available designs with adequately documented performance levels are proprietary in nature [Refs. 25 and 29].

Another option which is not in current use and which remains to be fully evaluated as to effectiveness is the lined wall concept. By lining the considerable wall/overhead area foreward of the engine inlet with suitable foam and lead septum material it may be possible to entirely eliminate the need for duct obstructing devices with consequent simplification of distortion control. Since considerable absorbing thickness could be provided at low cost in a test cell, this option must be considered. Preliminary analysis by the treatment manufacturer indicates that this method would be restricted to a vertical inlet arrangement. The lining material is available from commercial sources and it would be necessary to obtain their assistance in determining the type and quantity required [Ref. 29].

Any of these alternatives can provide the required acoustic control and except as noted do not restrict the selection of inlet position. Detailed investigation is required to evaluate the possible



trade-offs in cost, size, service life, and distortion. The construction contractor will require the services of a qualified acoustic engineer, but satisfactory inlet acoustic treatment can be provided at reasonable cost. Doelling and Bolt [Ref. 35], provide an excellent summary of calculation procedures for design use. Before final selection can be made the designer must, of necessity, consider compatibility with the aerodynamic requirements detailed in the next section.

## 2. Aerodynamics

Comprehensive design criteria are not available for this aspect of the inlet design. No general method is available for the prediction of streamline, pressure, or velocity patterns though these may limit the total test cell in its compatibility with future engines. Reference 12 is an example of a completed construction specification which ignores this requirement entirely and depends on luck for satisfactory operation. The designer has available the choice of:

- a. Inlet shape: horizontal, vertical, inclined, open ended or capped;
- b. Number of turns, radii and flow lengths;
- c. Shape of the flow dividers used in acoustic control;
- d. Duct shape: expanding, contracting, constant area; open or vane guided turns,
- e. Duct wall finish: protrusion streamlining, the shrouding of fittings and the installation of boundary layer trips or vortex generators [Ref. 36].



The following diverse factors must be considered in selecting from these options.

- a. Cost and availability of real estate at the proposed site.
- b. Effect of inlet stack height and position on the reingestion of exhaust gas.
- c. Required cell air flow capacity.
- d. Allowable pressure and velocity distortion of the flow at the engine inlet [Ref. 37].
- e. Allowable cell depression.
- f. Requirements for emergency airflow shut off to permit CO<sub>2</sub> flooding.
- g. Local weather conditions, especially winds.
- h. Construction cost per square foot of cross sectional area and foot of length.

Of these factors, a, g, and h, may be accurately determined following the selection of the construction site. Analysis of the effect of stack height and position requires that the exhaust treatment type and pollution control system be identified. In general, with exhaust directed vertically, increasing the inlet height and reducing inlet-to-exhaust separation distance reduces the probability of avoiding recirculation problems. A horizontal inflow naturally reduces the likelihood of exhaust gas capture [Refs. 38 and 39]. The references provide reasonably accurate prediction methods for proposed design susceptibility to recirculation.





Determination of the total inlet flow capacity requires identification of maximum projected engine requirements and facility type. With this available [Fig. 1], it is necessary to select the augmentation ratio for the cell. Again, this can not be freely chosen but is fixed by choice of exhaust treatment system since the various types have widely different requirements for excess air. Since a continuing trend toward higher exhaust temperature is evident in Section II excess air to cool this exhaust will go the same way. Since this capacity may limit the facility growth potential and excess capacity is low in maintenance cost, it should be maximized consistent with construction costs. References 37, 28, 32, 12, and 40 illustrate typical current and anticipated augmentation requirements. From these a total airflow capacity three times the maximum engine requirement can be justified.

Since test cell operation ideally simulates free atmosphere engine performance the approach velocity is limited in modern facilities to a maximum of 50 feet per second [Refs. 28, and 37]. This is an arbitrary limit, but is reasonable since increasing velocity above this point rapidly increases the cost of distortion control, increases cell depression and decreases the accuracy of thrust measurement data. Accepting this limit, cross-sectional area required is available and depression per foot of flow length may be accurately estimated using the standard duct flow loss techniques of Refs. 41, 42, and 43. Various depression limits have been used in design of current facilities but general agreement is found in considering the depression to



be a free variable and altering the design to change it only in the most extreme cases; i.e., those in which pressure loads approach the structural load limit [Refs. 37 and 40]. The effect of greatly increased mass flows on depression and required cross sectional areas is demonstrated in Fig. 8.

In the past, with these estimates, the designer could produce construction blueprints for the inlet. Prior to the introduction of the turbofan engine the production test cell was required to produce a specified quantity of air at a reasonable velocity at the engine inlet. Only the grossest mismatch of engine/cell sizes or the ingestion of objects other than air molecules could produce compressor stall, flow reversal, overtemp or unstable engine oscillation. Today, test cells can be and are built which have more than sufficient inlet flow capacity but which can not be used to test the engines for which they were designed [Refs. 37 and 10]. The condition responsible is non-uniformity of pressure or velocity distribution at the engine inlet. Turbofan engines, both high and low bypass, and special-use, lift type engines are the most sensitive to this distortion [Ref. 44], but when it exists it affects every engine tested to an unpredictable extent. Its sources are numerous and effectively include everything in the cell between the open atmosphere and the engine face which is in other than a straight smooth-walled duct [Refs. 37, 45, 46, 47, and 48].

The design of distortion free inlets is an empirical matter with even the most experienced contractors in the field [Ref. 34]. Until



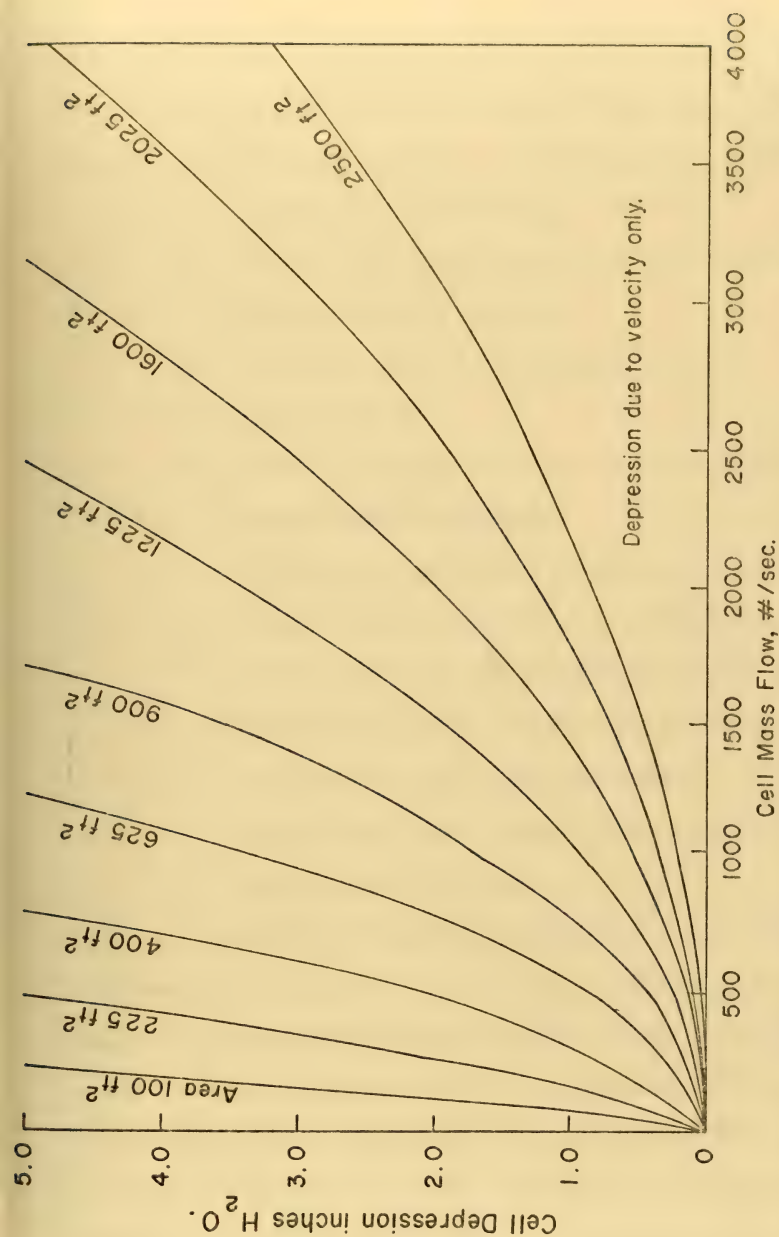


Figure 8. Effect of Increased Mass Flow on Cell Depression and Required Area.



a method becomes available to predict the flow distortion for a projected engine in a proposed cell with variable augmentation ratio, the designer must accept the necessity of the following restrictions:

- a. Minimize the number of turns in the inlet.
- b. Place no flow dividing surfaces in the inlet which are not absolutely necessary.
- c. Streamline all surfaces confining the flow or immersed in it.
- d. Provide flow length forward of the engine for vortex and wake damping [Ref. 33].
- e. Construct and test models of proposed designs [Ref. 49].
- f. Provide turning vanes [Ref. 34], and flow straighteners for cell operations near design flow capacity.
- g. Test the finished cell with reasonable completeness at all flow levels and augmentation ratios.
- h. Employ aerodynamic methods in the design of duct curves [Refs. 50 and 51].

Reference 33 indicates an empirically determined pressure distortion maximum of  $\pm 0.25$  in  $H_2O$ . The persistence of wakes generated by flow obstructions may be estimated with the methods of Refs. 52, 53, and 54. However, total distortion can not be accurately predicted and no fixed limits have yet been established by test cell operators or designers. Distortion indices have been published by many manufacturers for production engines. Definitions vary but each index may be





measured by pressure survey rakes located forward of the compressor face. The variation with engine speed of this index may be measured for a given engine type in a particular cell and the limit which will cause engine surge or stall is then available. Unfortunately, there is no method for predicting the value of the distortion index for a proposed cell design. Extensive investigation has also failed to establish useful correlations between test cell stall margin and that of the same engine installed in an aircraft [Ref. 55]. Therefore, the best the designer can now do is to conform to the above guidelines and include provisions for repeated aerodynamic monitoring of cell performance throughout the service life of the facility. Current research may vastly simplify this aspect of design and increase confidence in the final performance of future high capacity cells [Ref. 56]. For current installations distortion caused by inlet vortices may be reduced after discovery by the employment of wall or deck fences or aspirated plates [Ref. 36].

### 3. Maintenance and Safety

Aside from basic structural integrity of all components, the contribution of inlet design to safe cell operation has been in the provision for airflow shut off and filtering for fire fighting and protection of the engine from foreign object damage. This latter requirement is universally accepted and is met by various combinations of wire mesh duct screens and bellmouth covers. The designer may locate these screens as convenient but placement aft of distortion-producing



acoustic treatment will provide a bonus of a reduced requirement for flow mixing length. References 42 and 50 may be used to calculate pressure loss due to screening.

Though CO<sub>2</sub> flooding systems are available in many present test cells, there is less than complete agreement about the necessity of their incorporation in future facilities. Increased size and the greater CO<sub>2</sub> capacity required to effectively flood large cells has escalated the associated installation costs. Larger cross sections also imply longer operating times for hatch shut-offs and further reduce system effectiveness. Operator experience indicates that the Cardox flood system may itself be more of a hazard than the fires it is intended to prevent due to casualties possible from accidental actuation. Many aircraft powered by turbojet engines now incorporate quick shutdown systems and local application of extinguishing agents. Similar provisions in test facilities may eliminate the requirement for a quick-acting inlet shutoff. This is worth detailed investigation since it would remove the only inlet component requiring regular maintenance and would represent a considerable savings in construction cost [Refs. 16 and 34].

The cell access doors and their actuation systems are the other inlet components with maintenance requirements in a side loaded configuration. If the front loaded layout is selected, it may be necessary to include articulated acoustic treatment and flow straighteners which will increase loading time somewhat and be sources of



additional maintenance requirements. In either case, sliding or outward opening doors provide designed-in safety.

Inlet design can make a substantial contribution to overall cell performance and to reduction of operating costs by the inclusion of a mounting frame for air filtration panels. Passing the flow through a ten micron filter will increase the life of all cell components from acoustic sheet metal to temperature probes [Ref. 16]. These panels are low in cost and are reuseable; the increase in cell depression is minimal. The air quality at nearly all facility sites is now poor enough to make this a profitable addition to new designs; this quality is not likely to improve much in the future.

## B. TEST SECTIONS

### 1. Engine Handling and Access

Efficient operation of production type test cells require that the non-running time of the engine in the cell be minimized. The engine-test bed adapter system is the best means of reducing this time and has demonstrated satisfactory performance at many modern facilities. Since the adapter is attached to the engine in the preparation area the handling system must transport the completed unit. Selection of the optimum handling method requires consideration of the following factors:

- a. Tracked dollies prevent damage to concrete decking and eliminate traffic accidents that can occur with free dollies, but they are relatively inflexible in



- accepting widely varying engine sizes. They are also reasonably complex when used with engine-cell adapters and may require more maintenance than overhead handling systems of equal capacity.
- b. Free dollies may require special high cost decking for use with large, heavy engines and, when designed to handle the engine/adaptor combination, they may not be suitable for general use elsewhere in the repair facility.
  - c. Bridge cranes lack the ability to serve both the test cell and a large preparation area. They also require larger and more expensive cell access doors.
  - d. The overhead monorail, either powered or free, minimizes access door size, can be tracked to multiple prep area stations, is suitable for the engine/adaptor combination, can incorporate the hoisting unit required for cell loading, is flexible in size and shape capacity, and allows required maintenance to be performed outside the cell. This system is in operation [Ref. 11], in present facilities; the only difficulty has been the effect of the rail on inlet aerodynamics. A streamlined track shroud or submersion in the overhead surface may reasonably be expected to eliminate unacceptable flow distortion.





Access to the installed engine must be convenient and safe. The access structure must not produce flow distortion or recirculation during test operation and must be adjustable in height and lateral position. Current systems utilize access structures which retract into the interior cell surfaces [Refs. 16 and 33]. Deck mounted service stands will be continually subject to corrosion damage from spilled engine fluids and cleaning solvents, and they must support transport dollies if an overhead system is not employed. A valuable addition to operational efficiency can be made by the designed inclusion of storage space for servicing and troubleshooting equipment which is convenient to the work area. Adequate lighting of the side and bottom engine surfaces is essential and at some sites the installation of radiant heating units can greatly increase efficiency and safety.

## 2. Acoustic

In current test cells it is the acoustic portion of the engine environment which is least similar to that of the aircraft-installed engine. Reflection from the smooth concrete surfaces surrounding the engine subjects the engine casing and external accessories to acoustic power levels several times those present in an aircraft. No reliable data on damage caused by this is available but it is certain that it is not beneficial. Some operators subjectively estimate that a 10-15% reduction in component life is attributable to this source. New cells should be designed to minimize the acoustic energy reflected onto the test engine either by absorbing it at the wall surface or directing it away



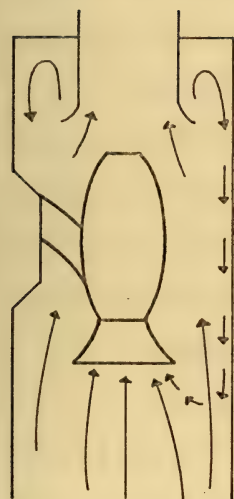
from the test section. Reference 57 illustrates the substantial reduction possible with commercial absorbent materials. The effectiveness of directionally reflective surfaces is illustrated in Ref. 39; this option has the advantage of nominal cost in new construction.

### 3. Aerodynamics

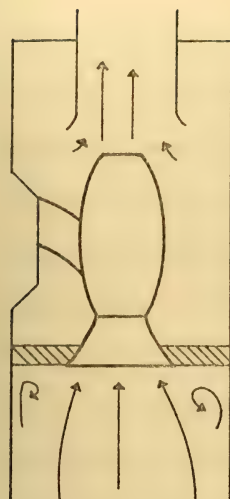
The primary requirement for the test section is that the flow remain unidirectional and without recirculation of engine exhaust. Aft of the engine bellmouth there is no further necessity for streamlining or shrouding equipment except that even small variations of pressure along the engine casing may produce variation in the measured thrust. This will be minimized by keeping the exposed surface area between the engine and the thrust bed to a minimum and, if constant, it can be included in cell correlation factors [Refs. 8 and 37].

When the augmentation ratio is high, there is little likelihood of recirculation. When little or no augmentation air is used, the control of recirculation is more difficult and, to be flexible, new facilities must be designed for possible operation in the zero augmentation mode [Ref. 37]. Figure 9 illustrates the primary alternatives for recirculation control. The septum wall provides positive control but must be considered as a last resort due to the mechanical complexity involved in making it removable, useable with different engine inlets, and strong enough to resist the considerable pressure loading which is possible. The second alternative requires that excess air be drawn past the engine even when it is not required for exhaust cooling or

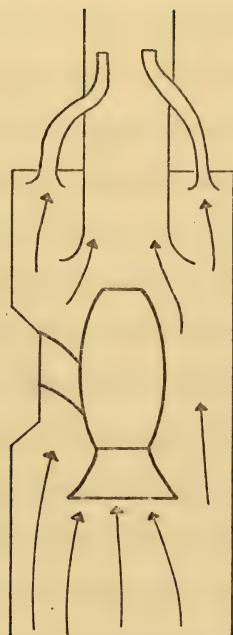




Augmentation



Septum Wall



Passive Exauster

Figure 9. Recirculation Control Options.



mixing. Since this is needed only while the engine is in operation, it is logical to make the engine exhaust the power source and design the system to be entirely passive. An active exhauster powered by a separate electric motor is possible, but the flow capacity required and the additional cost and maintenance make it less than attractive. The drawback to inclusion of the passive venturi powered system is that the initial motivation for operation with a low augmentation ratio may be reduction of the flow volume to be handled by a pollution control system. If the afterburner method of pollution control is to be used the exhauster air could be added to the exhaust aft of the secondary combustion zone. In any system, if the volume flow required for control of recirculation is low enough, inclusion of the passive exhauster must be considered since it has the advantages of low initial cost and minimum maintenance requirements [Ref. 33].

Installation of cell instrumentation with the capacity to detect recirculation is a design feature which will return an excellent profit on a small initial investment by ensuring test reliability and preventing the accumulation of explosive mixtures when future engine-augmenter positions are varied.

#### 4. Instrumentation and Mounting

A key feature of the instrumentation design is flexibility. Effective use of the engine adapter system requires that the permanent test cell portion of the equipment require little or no modification when new engines are introduced. Each adapter will be customized to a





particular engine but all must appear identical to the test bed. This demands that the original design have sufficient capacity to accept the number and type of data transmission channels required by future engines and refined test techniques. References 12, 16 and 28 illustrate current estimates of this requirement; recent experience indicates that the savings possible by limiting this capacity will almost certainly be temporary ones, since excess capacity is free of maintenance cost and can, in fact, greatly reduce cell down-time by permitting rapid shift to alternate channels when malfunctions occur. Maintenance can then be performed at scheduled times. The importance of this capability cannot be overemphasized since most operators report that the majority of cell down-time results from instrumentation malfunctions.

Though cell accessibility may be complicated by the use of the overhead thrust bed, its advantages more than compensate for this, and it is now recognized as the best design for future test cells. Among these advantages are: natural similarity to aircraft engine mounting methods, ready compatibility with monorail handling, freedom from corrosion by collected fluids, flexibility in engine positioning, and the availability of advanced design experience. It is possible to utilize a single step plug-in of the adapter to the test bed but experience indicates that separating the connection of the physical support from the plug-in of the instrumentation leads enhances system reliability [Ref. 16].

For facilities required to anticipate a wide spectrum of



thrust levels, it is possible to improve thrust measurement accuracy by using a three component system: test frame, thrust bed and engine adaptor. With this arrangement the thrust bed may be changed to one having flexures with maximum sensitivity in the desired range [Ref. 16]. Investigation of the possibility of eliminating the direct thrust measurement system has shown that while it is technically feasible, the savings in engineering complexity are small and are offset by increased requirements for other types of instrumentation. In the view of most users, deletion of the direct thrust measurement system is not justified [Refs. 12, 16, and 39].

#### 5. Auxiliary Subsystems

One of the most persistent failures in test cell design has been lack of subsystem growth potential. Rapidly increasing fuel consumption rates have made extensive rework of some facilities necessary and restricted the operation of others [Refs. 12 and 16]. At several installations the supply of starting air has proven inadequate almost before the cell was placed in operation [Ref. 12]. For facilities requiring water for exhaust gas cooling or scrubbing it is imperative that future capacities be determined since they may well be double or triple those required to test current engines. In all these subsystems, doubling the design capacity increases initial cost only about 20 per cent while a similar change in an existing system may easily double the original cost and require extended facility closures.



In addition to sufficient capacity, the fuel system should be designed to permit future expansion to at least a two fuel operation [Refs. 2, and 58]. Again, providing this flexibility during design will cost far less than adding it later. Design of all subsystem controls should include maximum utilization of advanced control and monitor technology. The number and criticality of the subsystems which must be included in a turbojet test cell demand that careful attention be given to design of interlock controls providing fail-safe operation. There is no reason for operator error or an undetected malfunction to cause major damage to the engine or test facility. The electrical power dissipation, dynamometer and fire extinguishing systems should also be routed through a master interlock control.

### C. CONTROL CENTER

The choice of data acquisition method will establish the requirements for the design of this area. In a facility requiring manual data recording, 25-30 per cent of the total engine running time is occupied solely by data acquisition. Additionally, two to three minutes may elapse between the first and last data reading at each operating condition. Thus the justification for the higher cost of automatic data acquisition systems includes reduced cell time per engine (with accompanying reduction for fuel, utility and pollution abatement loads) and increased test credibility due to the simultaneity and accuracy of data.

Sufficient incentive exists for the inclusion of automatic data



scanning equipment in all future production test cells. It is possible to automatically acquire data and simply supply it as a printed record. But the nature of the data processing normally required is such that its inclusion within the automatic equipment is simple and effective. It can then be presented in a written format acceptable to the user [Fig. 10], or as real-time operator assistance. Further extension of data system sophistication is possible and may be justified in the following areas:

- a. Individual engine history records containing either rework/repair testing results or expanded to include in-service information [Ref. 59].
- b. Safety monitoring capability to provide warning of impending failure or to initiate shutdown or other corrective action.
- c. Operator assistance in the form of step-by-step procedural instructions and malfunction analysis.

The computer centered data system can also be operated in a closed loop mode with engines tested under fully automatic control [Refs. 58 and 16]. It is unlikely that this could be economically justified in future production type facilities, however, since manpower savings would be small (installation and repair still required) and the cost of a reliable system high.

Long range economy is best served by including in the initial system design excess capacity to permit processing of additional data





\*\*\*\*\* TFE - 731 ENGINE \*\*\*\*\*  
 GUARD SYSTEM DATA SERIAL NO. 7307  
 DATE 2' 7/72  
 TIME 39-22  
 PAMB 14.76  
 CYCLE 1  
 IDLE FOR 1 MIN

\*\* CALCULATIONS \*\*  
 N1C2 5789.0 PT2 14.76 WFCOR 197.13  
 N2C2 16233.5 TT2 140.4 TSEC 0.9065  
 N2/N1 2.804 FNCOR 202.17 PDWF -0.574  
 GEN POWER 0.000 HYD PUMP NO.1 PW 397.328  
 TOTAL EXT POWER 513.647 HYD PUMP NO.2 PW 116.318

\*\* MEASURED DATA \*\*  
 SPEEDS-  
 N1 (RPM) 5789.0 THRUST (LBS) 203.05 FUEL FLOW MAIN 193.00  
 N2 (RPM) 16233.5 POWER ANGLE 38.60 FUEL FLOW VERFY 199.13

PRESSURES - (PSI)  
 COMP DISCH 27.76 OIL TANK VENT 0.00 PT7 LPT DISCH 15.04  
 FUEL PUMP INLET 67.51 NO.6 BRG SCAV 0.00  
 F/O (OIL IN) 0.00 TOT ENG SCAV 0.00  
 FAN G/B(OIL IN) 47.07 OIL PUMP DISCH 0.00

TEMPERATURES - (DEG F)  
 FUEL 55.2 TT7 LPT DISCH 180 0.0 TT5 HPI DISCH 838.2  
 F/O (OIL IN) 0.0 TT7 LPT DISCH 181 0.0 HPC DISCH 0.0  
 FAN G/B(OIL IN) 135.4 TT7 LPT DISCH 184 0.0 SURGE VAL D 805 84.3  
 HYD PUMP IN 130.4 TT7 LPT DISCH 185 0.0 SURGE VAL D 806 0.0  
 FAN G/B SCAV 124.1 NO 4 BEARING 0.0  
 NO 4-5 BRG SCAV 151.0 NO 5 BEARING 168.7

VIBRATION - (MILS)  
 TURB VERT 0.680 COMP VERT 0.590 B-FAN ORB VERT 0.000  
 TURB HORIZ 0.070 COMP HORIZ 0.770 B-FAN ORB VERT 0.000

Figure 10. Typical Data System Output.



without major remodeling. Removeable flooring in the control area is an excellent means of providing both maintenance access and ease of modification. The sensitivity of electronic data systems to interference and damage from acoustic, vibrational, and electromagnetic energy exceeds that of the human operators and reinforces the necessity for the inclusion of appropriate types of shielding in the design of the control area [Refs. 12, 14, and 28].

Replacement of the viewing window by a closed circuit TV monitor simplifies the insulation problem and increases safety. To justify its cost, the video monitoring system must be capable of providing resolution and discrimination comparable to that of an operator present in the cell. With carefully considered lighting and placement, accurate color reproduction, magnification to a one foot focal distance, and full articulation it will be possible to eliminate the necessity for in-cell operator inspection. This could reduce run times and allow leakage checks at other than idle power settings. For some facilities the addition of a video recording capability to the monitor system may be advisable. Having low initial cost, adaptable to fully automatic control, and requiring little maintenance, a video tape recorder could provide accurate records of malfunctions and permit continuing studies of cell efficiency. A recorder could also supply effective training material for operators when new engine models are introduced or new test procedures are initiated.

Modular design of the control station and provision of ready



access to the installed equipment should be of prime concern to the designer [Refs. 16 and 28]. Some operators presently feel that audio monitor capability should be provided, and an earpiece adaptation of the required intercom system could be employed for this purpose.

#### D. AUGMENTER AND EXHAUST TREATMENT

##### 1. General

An efficient, flexible and reliable exhaust system is perhaps the most critical segment in test cell design, yet the present level of engineering sophistication in this area is still elementary. Justification for the above statement is the recent change in the design criteria of cell exhaust treatments. Early designs were primarily built to lower exhaust temperatures to levels that would not unacceptably shorten the life of installed noise abatement systems. This was accomplished by mixing the jet exhaust with secondary air. Past acoustic practices have been re-examined [Refs. 60, and 61], and in many cases stricter requirements have been formulated [Refs. 15, 12, 25, and 58].

Additionally, attention is now being focused on reducing the air pollution levels of jet engine test cells. Generally, test cells are placed in a different regulatory category than are jet aircraft themselves. They are classed with other stationary sources [Refs. 62, and 63].



## 2. Aerodynamics and Thermodynamics

A poorly designed augmenter system may be one that acts, as an unnecessarily powerful jet pump. In this situation too much secondary or cooling air is entrained with the engine exhaust, causing higher than designed cell airflows and cell depressions. Also, larger than design airflows will increase distortion levels and possibly disrupt smooth engine operation [Refs. 37, 15, and 6]. Large air flow can also cause errors in thrust measurement.

At the other end of the design spectrum is the system that fails to induce enough secondary airflow, and thereby fails to prevent the problem of recirculation of exhaust gases. Excessive exhaust temperature may also result.

The problem of excess secondary airflow has been encountered at several facilities. At North Island a flange has been added to the augmenter bellmouth, restricting the flow of secondary air. This is not a smooth design aerodynamically, and the capability of this facility to handle large bypass fan engines or other high flow rate engine types is severely limited with the present flow restriction. A second solution is to install orifice plates within the augmenter itself to reduce the available flow area [Ref. 20]. This type addition is slightly more flexible than the former since various size plates may be installed depending on the flow characteristics of the particular engine under test. These fixes are shown in Figure 11, a and b.

At the United Air Lines facility in San Francisco, secondary





airflow in their new large jet engine test facility has been estimated as being almost twice as high as was originally anticipated [Ref. 17]. This condition has not exceeded cell structural limits with the present engines being tested, (JT9D, CF6), but the cell performance with advanced technology engines which may reach the 100,000 pound thrust category will be marginal. This situation indicates the need for close attention to augmenter design and more thorough analysis of the ejector process.

Secondary air provides the necessary cooling of the engine exhaust and prevents recirculation. For a turbojet engine operating out of afterburner mode an augmentation ratio of 2:1 has been set as a reasonable design goal [Refs. 12 and 15]. Augmenter performance is a function of the area ratio of the augmenter and exhaust nozzle, the length of the augmenter, the position of the exhaust nozzle relative to the entrance of the ejector tube, and velocity ratio. Most recommended test cell augmentation ratios for fan engines vary from 0.25:1 to 0.5:1 for high bypass engines and up to 1:1 for low bypass types [Refs. 12, 15, 5, and 64]. Appendix A contains the standard definitions of augmentation ratio for turbojets and turbofan jets.

Besides its function of providing the means of mixing and cooling the engine exhaust, the ejector system must overcome the various pressure drops in the inlet and the exhaust systems. Figure 13 shows the general pressure pattern within the test cell. Basically, momentum is transferred to the secondary air, thereby increasing its pressure.



Studies have been made to determine the mixing characteristics of jet pumps [Refs. 65 thru 74]. These indicate that for each characteristic exhaust and secondary airflow combination there is an optimum length and diameter mixing tube. However, because of the cost of construction of the exhaust facilities many trade-offs must be made, and a flexible design must be selected that will work reasonably well over the range of engines to be tested.

A second method of cooling the exhaust is to use water spray cooling. This method is mandatory for engines operating in the afterburner mode, but may be used in other modes as well. Studies have been carried out [Refs. 15 and 27], which indicate the amounts of air, water or both which are required to cool exhaust gas temperatures to acceptable levels. When suitable amounts of water cooling are used, secondary airflow can become negligible. However, compromises must be made to determine the amount of water used. At the present time most of the water used in spray cooling is lost through the stack. At several locations, including NARF North Island, fresh water supplies are at a premium; availability may dictate the design option chosen.

Where water cooling is necessary and available, difficulties remain in devising means whereby the high temperature jet core may be thoroughly penetrated by water streams. It is known [Ref. 18], that even high pressure water jets have little success penetrating into the core of a high speed flow. Various designs have been developed, including concentric rings, water spargers and bounce sprays [Refs.



20, 19, and 75]. These designs, however, have not been optimized for facilities required to test widely varying engine types.

Matching augmenter characteristics to individual engines will be difficult, particularly where low augmentation ratios are desired.

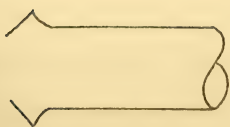
Variable area nozzles are common for afterburning engines. The exhaust from the fans of high bypass engines is at a relatively low energy level, and since it contains no products of combustion, separate ducting may be desirable. The Pegasus engine used in the Harrier aircraft requires complex ducting during test cell operation [Ref. 5].

Prevention of thermal damage to the augmenter must be considered. In the entrainment zone [Fig. 12], the walls are subject to radiant heating, while in the fully developed mixing zone they are heated by convection. Water jackets may be necessary during testing of afterburning or high turbine inlet temperature engines, particularly if the selected exhaust treatment system requires a low augmentation ratio.

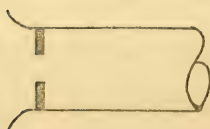
### 3. Acoustic Treatment

Noise sources that must be treated by exhaust systems are: turbomachinery generated noise, combustion noise, turbulent noise generated by the interaction of the jet exhaust and the secondary air and the turbulence in the exhaust itself [Refs. 76-81]. In the entrainment zone the shear stresses are high and the turbulence level is relatively low, creating most of the high frequency noise emanating





(a)



(b)

Figure 11.

Augmenter Flow Restrictions at Two Navy NARFs.

(a) Flange installation at NARF North Island

(b) Orifice installation at NARF Alameda

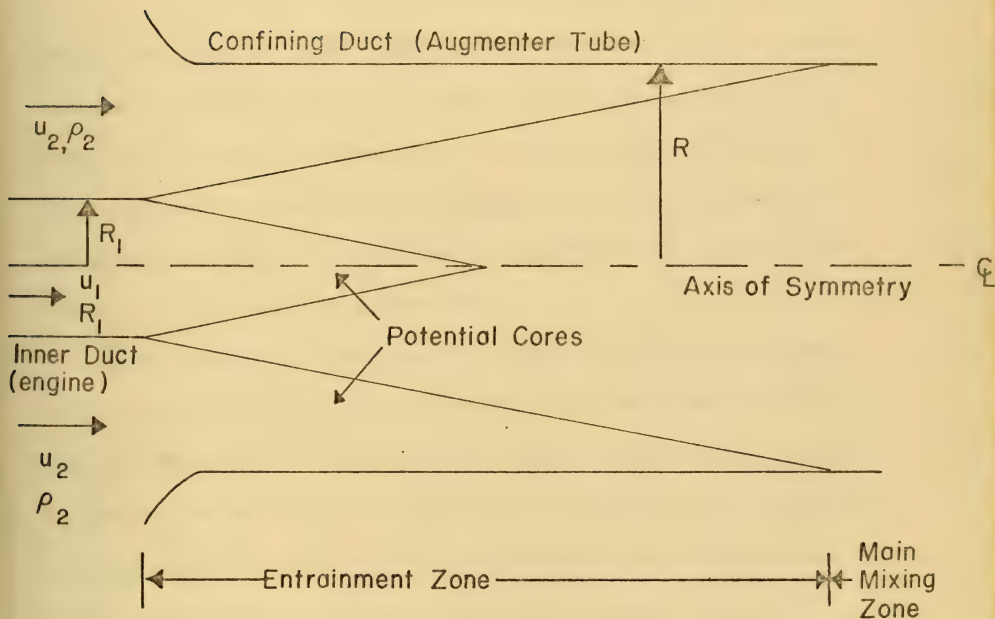


Figure 12. Jet Mixing Zones.





from the jet [Ref. 82]. Most of the low frequency sounds, those which contribute the most to the overall sound level, come from the portion of the exhaust beyond the potential core; the peak of this sound is at a wavelength about three times the diameter of the jet [Ref. 82]. It is this low frequency sound that is most difficult to attenuate. The higher frequency noise of machinery is easily abated with standard techniques which include baffles of all types, lined passages and bends, and tubular exhaust passages [Refs. 15, 33, and 37].

The properly designed augmenter can contribute to the overall reduction of noise; experimental results [Ref. 83], have shown that jet noise can be reduced by a factor of 5 (7db) in an ejector noise suppressor. It was also shown that the initial mixing conditions and the length of the injector are more important factors in obtaining this attenuation than the area ratio of the tube and jet or the position of the primary jet relative to the ejector inlet.

Methods of breaking up the continuity of the jet and increasing the frequency of the exhaust noise are discussed in Section IV. The utilization of a colander in the form of a cone or a cylinder is presently preferred over other options in modern cell designs. It has been found by experience that a hole size 1-1/4 inch in diameter is the smallest practical size [Ref. 15]. Holes smaller than this tend to be easily blocked due to impurities in cooling water as well as particulate matter present in the engine exhaust. Standard practice has been to uniformly space the holes over the surface of the colander, with total hole area



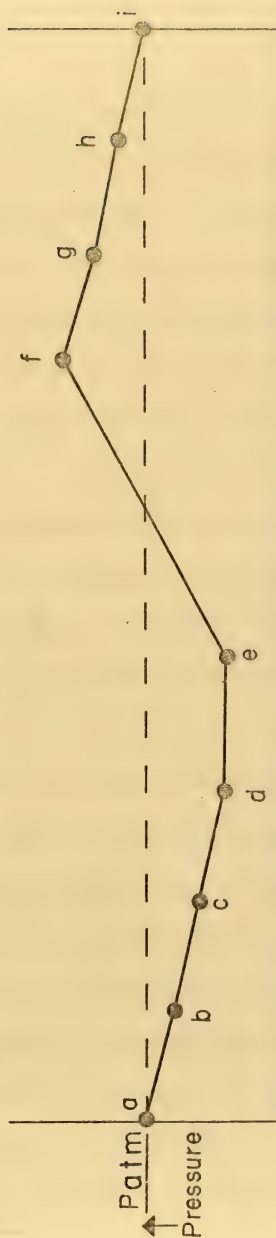
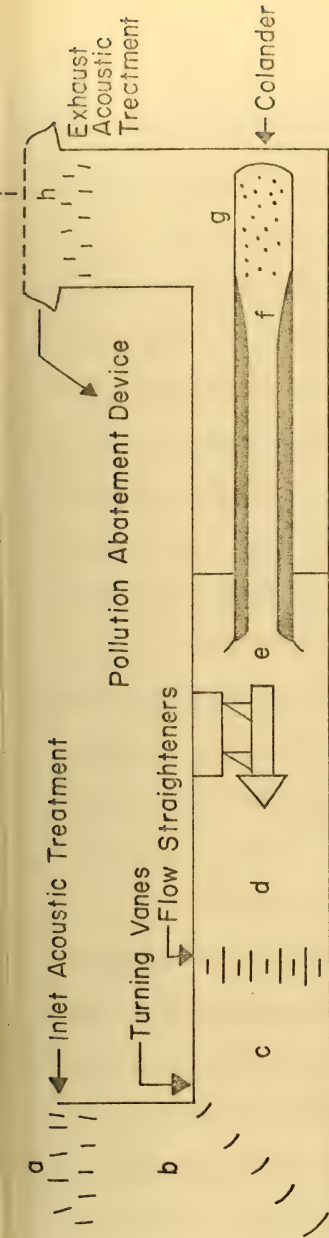


Figure 13. Test Cell Pressure Profile.



40 to 60 per cent in excess of the cross sectional area of the augmentor tube itself [Refs. 21 and 15].

An exception to this practice has been introduced in some smaller Navy "C" cells [Ref. 21 and Fig. 5]. In these cells holes were placed only in the lower half of the colander. This design has exhibited a serious shortcoming in that flow through the exhaust stack is very non-uniform; in fact, some points in the stack exhibit zero velocity. This causes portions of the acoustic treatment to be exposed to higher than design flow rates, thereby shortening useful life and decreasing overall performance.

Analysis must be done during design to ensure adequate flow conditioning over the operational range of the proposed test cell. The designer must ensure that enough pressure rise will be obtained to overcome any flow blockage that may be present under all operating conditions.

Unwanted acoustic energy may be generated by obstructions present in the ejector assembly. These include spray rings or nozzles, diffuser rings and any other hardware installations. These obstructions increase the turbulence level of the flow, thereby increasing the noise sources within the flow. The merits of each proposed installation must be weighed according to the use intended for the individual test cell. Care must be taken that natural frequencies of installed components are not activated by the driving frequencies of the flow.

Possible exhaust stack treatments are as varied as those



intended for use in the inlet. Options include lined bends and passages, tubular mufflers, sinuous passages or straight passages [Refs. 28, 29, and 15]. Steel Helmholtz resonators have been investigated by General Electric [Ref. 15], and have been found to be unsatisfactory for their own use; this approach has been successfully taken by Aero Systems Engineering, however [Ref. 39]. Differences are in the cell utilization of the two operators, and in the acoustic characteristics of the engines tested.

A primary concern is to develop a system which will withstand a moderate range of temperatures and wide range of velocities. Most installations have been designed to withstand exhaust stack temperatures in the 450-550° F range, with a maximum of 600° [Ref. 15]. At one time NARF North Island attempted to maintain temperatures below 200° in the non-afterburning mode by water cooling. However, it was impossible, with the existing water spray design, to operate the afterburner and maintain stack temperatures below 450°, and the installed acoustic treatments were subjected to such severe thermal shock that their useful life was drastically shortened. Within practical limits a constant stack temperature should be maintained in all test modes.

Because of the varied sizes and characteristics of engines that will be tested in new construction test cells, consideration should be given to the possibility of providing variable area exhaust stacks. Methods of accomplishing this vary from simply blanking unnecessary portions of the stack with pre-fitted metal shutters according to the





flow requirements of the engine under test to a movable cover over the stack opening which is programmed to provide optimum flow area (and available acoustic treatment) for a given engine power level. By designing the basic exhaust system to handle the largest forecast airflow with the additional capability of efficiently handling much lower flows the problem of test cell obsolescence caused by advances in engine technology can be avoided.

#### 4. Emission Control Devices

In the future, major design effort must be devoted to pollution abatement systems. It has been established by Executive Order 11282, May 26, 1966, that Federal installations comply with local environmental protection requirements. At the present time most emission requirements which are applicable to test facilities deal with the particulate emissions which cause visible pollution. Future legislation will limit emission levels of invisible noxious gases, carbon monoxide, oxides of nitrogen and sulfur dioxide. Studies have been conducted to determine exhaust emissions of gas turbine engines [Refs. 63, and 84-89], and although the exact emission levels are not agreed upon, most figures mutually agree on an order of magnitude basis.

The abatement system chosen for test cell operation must first remove visible particulate emissions. California legislation limits the deviation from a maximum of 20 per cent obscuration (#1 on the Ringleman scale) to three minutes out of every hour.



Except at idle, gas turbine engines emit very low levels of unburned hydrocarbons and CO, so that attempts to reduce these should concentrate on low flow rate conditions [Ref. 84].

By 1975 Los Angeles County will limit emission of oxides of nitrogen to 225 ppm [Ref. 62]. New developments in engine technology resulting in high pressure ratios and high combustion temperatures have raised the levels of these oxides in engine exhausts [Ref. 84]. The chosen abatement system must at the very least not add to these levels and ideally should reduce them.

The installed system must be able to remove unburned fuel from the exhaust flow. Estimates are that in the afterburner mode turbojets exhaust about 10 per cent unburned fuel. Also, the ability must be retained to purge unwanted fuel from the exhaust drainage system. Prior to light-off it is Navy practice to "dry run" the engine; that is, the engine is windmilled and the throttle fully opened to check for leaks. This results in relatively large amounts of fuel being dumped directly into the exhaust system.

Emissions of sulfur dioxide will not be a problem as long as the current restrictions on sulfur content of fuel are maintained. Present restrictions limit the sulfur content to .3 per cent, and most fuels contain even less.

Although advances have been made in combustor technology, completely clean jet engines are not yet a reality. NARF Alameda was recently cited in violation of local standards while testing a high



time engine configured with "clean" combustor cans. One source [Ref. 63], theorizes that reactions within the cell exhaust system change the character of particulate emissions, either in size or number, so that visibility obscuration is greater at the test cell exhaust stack than at the engine tailpipe.

Interim solutions for reducing smoke involve the use of fuel additives. United Air Lines in San Francisco utilizes CI-2 in their testing. Additives coat engine hot section parts, and the effect of adding heavy metallic vapors to the exhaust is under continuing investigation by the EPA.

Early studies of pollution abatement systems have resulted in the selection and development of a nucleation scrubber [Ref. 75]. Other devices analyzed include filtering devices, venturi scrubbers and electrostatic precipitators. These have been evaluated as unsatisfactory from considerations of safety, flexibility and economy in Ref. 75.

Filtering devices alone present problems because of their tendency to become clogged by particles entrained in the exhaust. Additionally, they require extremely low flow velocities, and are not effective in removing noxious gases.

The primary drawback to the venturi system is its inability to operate efficiently over greater than a 10 per cent interval away from its design point, which is an unacceptable restriction in light of the fact that air flows vary as much as sixty to seventy per cent from idle to full power setting. A possible solution to this would be the



installation of a bank of venturis, entailing high initial costs and complicated flow controls.

The present shortcoming of electrostatic precipitators is the inability to completely prevent fuel buildup on and around the electrodes; this condition creates the danger of an explosive discharge. Also, these systems cannot remove noxious gases or oxides of nitrogen.

Nucleation scrubbers work by process of creating large particles by condensation of vapor from a saturated vapor. The nucleates are the particulate matter already present in the exhaust. The enlarged particles are then removed by impaction in the scrubbing system. A prototype scrubber system developed by Dr. A. Teller (Pat. #3,324,630) has been installed by the Navy at NARF Jacksonville. This particular scrubber has the capacity to handle large changes in flow volume, can reduce noxious gases and unburned fuel and with modification can remove much of the oxides of nitrogen and sulfur if such action is required. Installation of this scrubber is also anticipated at NARF Norfolk. The primary drawback at present with the scrubber system is its high initial costs. At its present level of development this system is not considered the ideal solution, and investigation is being carried out in other areas as well.

The nucleation scrubber as well as the other alternatives discussed are all similar in that they function by physically removing particulates and unwanted gases; a second class of installations acts





by converting unwanted pollutants to harmless chemical species.

These include afterburners and catalytic converters.

Northern Research and Engineering Corporation has proposed a thermal converter installation for test cells [Ref. 62]. This reference is a comprehensive discussion of the feasibility of such an installation and the justification for Navy procurement in light of future requirements for pollution control. At the present time much work remains to be done in conducting recommended studies and testing.

The installation of a converter system will require close matching of the test section, engine and exhauster itself since the proposed system requires a low augmentation ratio.

The final selection of an abatement system will be based on its flexibility and economy. It must be able to operate over a wide range of exhaust velocities and temperatures. The initial cost of procurement and installation must be low, as must the cost of operation and upkeep. The system must be reliable enough to allow firm scheduling of cell down time with the minimum amount of unscheduled maintenance. An additional factor will be the ease with which the abatement system may be retrofitted to existing test cell structures.

The creation of secondary pollution must be avoided. Thermal pollution of natural water supplies is a real possibility in systems requiring heavy cooling. Also to be avoided is the creation of additional, unwanted noxious gases or other undesirable products of combustion if an additional combustion process is used.



Maximum allowable temperatures, pressures and velocities will dictate the level of required protection of hardware exposed to the jet exhaust. Because of the temperatures encountered during after-burner runs it may become necessary to water cool certain exposed parts. Refractory linings have been considered, but were rejected for economic reasons [Ref. 62].

Complete acoustic analysis must be completed to ensure that the natural frequencies of equipment exposed to the flow not be excited by the frequencies of turbulence generated noise.

Finally, the design of adjustable components should be kept as simple as possible. Operators are wary of too much gadgetry in test cell design [Refs. 17 and 20], and cell down time increases with the addition of mechanical sophistication. All facilities must be designed to operate with the minimum amount of required upkeep.



## APPENDIX A

### Equivalent Augmentation Ratio for Turbofans

Test Cell Augmentation ratio is defined as

$$A = \text{Augmentation ratio} = \frac{m_i - m_e}{m_e}$$

where  $m_i$  = total mass flow in the inlet stack

$m_e$  = mass flow passing through engine

Bypass ratio for a turbofan is defined as

$$B = \frac{m_e - m_c}{m_c}$$

where  $m_c$  = mass flow through engine core

Cooling air for a turbojet is  $m_i - m_e$ . For a turbofan cooling air is  $(m_i - m_e) + (m_e - m_c)$ , if energy added by fan is neglected.

Manipulation leads to

$$A_{\text{eff}} = A + B + AB = \frac{m_i - m_c}{m_c}$$



## Appendix B

### Firms with Experience in Test Cell Design

The following firms are known to have valuable expertise in areas pertinent to test cell design. The list is by no means complete, but it will give the potential operator an excellent starting point for contacts regarding facility design. Additionally, the customer should contact the large number of test cell operators to ascertain any problems which inevitably arise. These operators include airline overhaul facilities, engine manufacturers and military rework facilities.

#### 1. Aerodynamics and Engineering

Aero Systems Engineering Inc.  
358 E. Fillmore Avenue  
St. Paul, Minn. 55107

Burns and Roe Inc.  
9800 South Sepulveda Blvd.  
Los Angeles, California 90045

FluidDyne Engineering Corp.  
5900 Olsen Memorial Highway  
Minneapolis, Minn. 55422

Gustav Getter Associates  
524 North Avenue  
New Rochelle, New York 10801

Northern Research and Engineering  
200 Vassar Street  
Cambridge, Mass.

Price-Clark Industries  
420 South Pine Street  
San Gabriel, California 91776

Sverdrup and Parcel and Associates  
800 North 12th Blvd.  
St. Louis, Missouri 63101





2. Acoustic Controls

Aeroacoustics Corp.  
P. O. Box 65  
Amityville, New York 11701

Bolt, Beranek and Newman Inc.  
50 Molton Street  
Cambridge, Mass.

Industrial Acoustics Company  
380 Southern Blvd.  
Bronx, New York 10454

Koppers Company Inc.  
400 Commonwealth Avenue  
Bristol, Va. 15219

R.I. Corporation  
499 West 2nd Street  
Ogden, Utah 84402

The Soundcoat Company, Inc.  
175 Pearl Street  
Brooklyn, New York 11201



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DATA SUMMARY  
ORDERED BY CONFIGURATION NUMBER

CONFIG NUMBER	M	ENG VEL	RADIAL DISTORT.	CIRCUM. DISTORT.	K <sub>D</sub>	AUG. RATIO
1113.113222	0.659	101.860	0.0007 SAT	0.0428UNSAT	0.9248	0.0
1113.213111	0.669	103.373	0.0017 SAT	0.0428UNSAT	0.4761	0.0
1113.213223	0.518	80.038	0.0017 SAT	0.0430UNSAT	0.9272	0.0
1113.313222	0.673	104.047	0.0011 SAT	0.0427 SAT	0.2608	0.0
1113.413222	0.667	103.068	0.0038 SAT	0.0427 SAT	0.3635	0.0
1113.413222	0.691	106.846	0.0012 SAT	0.0397 SAT	0.4010	0.0
1113.413543	0.495	76.478	0.0019 SAT	0.0432UNSAT	1.5234	3.635
1121.113222	0.672	103.883	0.0006 SAT	0.0399 SAT	1.1141	0.0
1121.113342	0.493	76.219	0.0048UNSAT	0.0437UNSAT	1.8473	1.197
1121.213222	0.665	102.835	0.0031 SAT	0.0433UNSAT	0.9334	0.0
1121.213342	0.492	76.044	0.0037UNSAT	0.0435UNSAT	2.0933	1.210
1121.313222	0.672	103.800	0.0006 SAT	0.0428UNSAT	0.7879	0.0
1121.313342	0.489	75.664	0.0042UNSAT	0.0435UNSAT	1.0884	1.425
1121.413222	0.680	105.098	0.0016 SAT	0.0397 SAT	0.5731	0.0
1122.112222	0.665	102.840	0.0006 SAT	0.0397 SAT	0.6558	0.0
1122.113542	0.473	73.467	0.0049UNSAT	0.0473UNSAT	5.9342	2.871



CONFIG NUMBER	M	ENG VEL	RADIAL DISTORT.	CIRCUM. DISTORT.	K D	AUG. RATIO
1131.113222	0.651	100.642	0.3012 SAT	0.0400 SAT	0.6798	0.0
1131.113223	0.517	79.938	0.0013 SAT	0.0429UNSAT	0.6386	0.0
1131.213222	0.665	102.824	0.0013 SAT	0.0428UNSAT	0.6107	0.0
1131.213442	0.478	74.592	0.0058UNSAT	0.0488UNSAT	7.2430	3.419
1131.213543	0.463	72.185	0.0056UNSAT	0.0479UNSAT	7.1440	4.374
1131.313222	0.666	103.011	0.0020 SAT	0.0428 SAT	0.8638	0.0
1131.413222	0.675	104.380	0.0012 SAT	0.0428UNSAT	0.5851	0.0
1131.413223	0.519	80.297	0.0009 SAT	0.0397 SAT	0.2304	0.0
1132.113222	0.673	104.042	0.0017 SAT	0.0427 SAT	0.4863	0.0
1132.113542	0.477	73.851	0.0043UNSAT	0.0448UNSAT	2.0010	2.994
1132.413222	0.662	102.366	0.0022 SAT	0.0427 SAT	0.7981	0.0
1141.213222	0.610	94.279	0.0048UNSAT	0.0432UNSAT	1.5663	0.0
1141.213223	0.489	75.636	0.0011 SAT	0.0434UNSAT	0.8138	0.0
1141.313222	0.606	93.694	0.0036UNSAT	0.0431UNSAT	0.9948	0.0
1141.413222	0.615	95.102	0.0040UNSAT	0.0429UNSAT	0.9320	0.0
1142.113222	0.592	91.516	0.0022 SAT	0.0405 SAT	1.2020	0.0
1145.113222	0.593	91.633	0.0025 SAT	0.0431UNSAT	1.5177	0.0
1152.113222	0.660	102.017	0.0012 SAT	0.0428UNSAT	0.7284	0.0
1213.113222	0.664	102.559	0.0005 SAT	0.0428UNSAT	0.7936	0.0
1213.113223	0.523	80.814	0.0017 SAT	0.0428 SAT	0.2303	0.0
1213.113543	0.511	79.355	0.0067UNSAT	0.0456UNSAT	6.3772	3.542
1213.213142	0.518	80.091	0.0012 SAT	0.0432UNSAT	0.8522	0.0
1213.213222	0.672	103.857	0.0017 SAT	0.0428UNSAT	0.8828	0.0





CONFIG NUMBER	M	ENG VEL	RADIAL DISTORT.	CIRCUM. DISTORT.	K D	AUG. RATIO
1213.213223	0.519	80.217	0.0009 SAT	0.0430UNSAT	0.5880	0.0
1213.313222	0.676	104.564	0.0021 SAT	0.0428 SAT	0.7643	0.0
1213.313342	0.501	77.456	0.0019 SAT	0.0435UNSAT	1.6468	5.380
1213.413142	0.511	79.051	0.0019 SAT	0.0428UNSAT	0.7996	0.0
1213.413142	0.585	90.443	0.0038 SAT	0.0398 SAT	0.6386	0.0
1213.413222	0.669	103.394	0.0013 SAT	0.0426 SAT	0.4594	0.0
1213.413223	0.522	80.649	0.0015 SAT	0.0427 SAT	0.2015	0.0
1213.413543	0.501	77.469	0.0010 SAT	0.0398 SAT	0.4407	3.588
1221.113142	0.521	80.476	0.0008 SAT	0.0399 SAT	0.6512	0.0
1221.113222	0.670	103.574	0.0036 SAT	0.0399 SAT	0.7268	0.0
1221.113342	0.491	76.016	0.0040UNSAT	0.0441UNSAT	1.9822	1.201
1221.213222	0.667	103.083	0.0020 SAT	0.0427 SAT	0.6362	0.0
1221.213342	0.490	75.847	0.0035UNSAT	0.0436UNSAT	1.7254	1.213
1221.313222	0.674	104.160	0.0003 SAT	0.0428UNSAT	1.3878	0.0
1221.313342	0.492	76.086	0.0032 SAT	0.0438UNSAT	1.6497	1.417
1221.413222	0.679	104.966	0.0009 SAT	0.0397 SAT	0.4455	0.0
1222.112222	0.669	103.435	0.0014 SAT	0.0396 SAT	0.4508	0.0
1222.113222	0.660	102.017	0.0038 SAT	0.0426 SAT	0.2627	0.0
1222.113542	0.480	74.599	0.0075UNSAT	0.0450UNSAT	3.4913	2.871
1222.313142	0.490	75.805	0.0019 SAT	0.0400 SAT	0.6445	0.0
1222.313542	0.461	71.367	0.0055UNSAT	0.0437UNSAT	1.4443	3.120
1231.113222	0.651	100.653	0.0006 SAT	0.0399 SAT	0.7639	0.0



CONFIG NUMBER	M	ENG VEL	RADIAL DISTORT.	CIRCUM- DISTORT.	K <sub>D</sub>	AUG. RATIO
1231.113222	0.686	106.008	0.0000 SAT	0.0429UNSAT	1.2759	0.0
1231.113223	0.535	82.778	0.0005 SAT	0.0400 SAT	0.5463	0.0
1231.213222	0.668	103.203	0.0013 SAT	0.0427 SAT	0.5839	0.0
1231.313222	0.671	103.708	0.0009 SAT	0.0427 SAT	0.6156	0.0
1231.413222	0.677	104.620	0.0009 SAT	0.0397 SAT	0.6093	0.0
1232.113222	0.676	104.482	0.0017 SAT	0.0427 SAT	0.6962	0.0
1232.113223	0.526	81.275	0.0013 SAT	0.0428 SAT	0.5152	0.0
1232.313222	0.669	103.388	0.0015 SAT	0.0427 SAT	0.5738	0.0
1232.413222	0.665	102.731	0.0022 SAT	0.0427 SAT	0.5294	0.0
1232.413223	0.532	82.208	0.0016 SAT	0.0397 SAT	0.3593	0.0
1232.513222	0.665	102.793	0.0017 SAT	0.0427 SAT	0.7684	0.0
1241.413222	0.613	94.697	0.0053UNSAT	0.0429UNSAT	1.1393	0.0
1241.513222	0.616	95.226	0.0015 SAT	0.0432UNSAT	1.7527	0.0
1242.113222	0.588	90.914	0.0029 SAT	0.0406 SAT	1.5013	0.0
1245.113222	0.590	91.289	0.0023 SAT	0.0405 SAT	1.5154	0.0
1252.113222	0.660	102.085	0.0010 SAT	0.0398 SAT	0.5323	0.0
1313.113222	0.654	101.076	0.0009 SAT	0.0431UNSAT	1.4935	0.0
1313.213222	0.667	103.192	0.0022 SAT	0.0433UNSAT	1.3662	0.0
1313.313222	0.670	103.626	0.0017 SAT	0.0398 SAT	0.6598	0.0
1313.313342	0.458	70.841	0.0055UNSAT	0.0442UNSAT	1.3388	5.887
1313.413222	0.664	102.606	0.0017 SAT	0.0397 SAT	0.4789	0.0
1313.413543	0.481	74.334	0.0036UNSAT	0.0401 SAT	0.6303	3.740
1321.113142	0.519	80.231	0.0011 SAT	0.0430UNSAT	0.9013	0.0



CONFIG NUMBER	M	ENG VEL	RADIAL DISTORT.	CIRCUM- DISTORT.	K <sub>D</sub>	AUG. RATIO
1321.113222	0.663	102.559	0.0026 SAT	0.0431 SAT	1.1816	0.0
1321.213222	0.667	103.109	0.0024 SAT	0.0430UNSAT	1.2132	0.0
1321.313222	0.666	102.990	0.0021 SAT	0.0430 SAT	1.2651	0.0
1321.413142	0.511	78.997	0.0027 SAT	0.0431UNSAT	0.9284	0.0
1321.413222	0.676	104.553	0.0020 SAT	0.0428UNSAT	0.7551	0.0
1321.413223	0.519	80.297	0.0016 SAT	0.0428UNSAT	0.7567	0.0
1321.413543	0.483	74.749	0.0040UNSAT	0.0441UNSAT	2.6631	4.125
1322.313142	0.499	77.207	0.0027 SAT	0.0402 SAT	0.5707	0.0
1322.313542	0.445	68.824	0.0047UNSAT	0.0401 SAT	0.7908	3.234
1331.113222	0.647	100.030	0.0015 SAT	0.0427 SAT	0.8420	0.0
1331.113223	0.529	81.753	0.0005 SAT	0.0432UNSAT	0.9666	0.0
1331.213442	0.485	75.678	0.0072UNSAT	0.0488UNSAT	8.1328	3.367
1331.213543	0.461	71.769	0.0032 SAT	0.0484UNSAT	7.8237	3.761
1331.313222	0.662	102.283	0.0016 SAT	0.0427 SAT	0.8257	0.0
1331.413222	0.674	104.124	0.0007 SAT	0.0397 SAT	0.7611	0.0
1332.113222	0.670	103.538	0.0027 SAT	0.0428UNSAT	1.1801	0.0
1332.113542	0.465	71.940	0.0044UNSAT	0.0436UNSAT	1.4225	3.001
1332.413222	0.661	102.116	0.0020 SAT	0.0427 SAT	0.4180	0.0
1341.113142	0.485	74.948	0.0026 SAT	0.0431 SAT	0.7744	0.0
1341.113543	0.131	21.323	0.0019 SAT	0.0590UNSAT	1.2712	8.303
1341.213222	0.606	93.620	0.0045UNSAT	0.0430UNSAT	1.2245	0.0
1341.313222	0.606	93.626	0.0030 SAT	0.0431UNSAT	1.2006	0.0
1341.413222	0.610	94.291	0.0041UNSAT	0.0430UNSAT	1.1878	0.0



CONFIG NUMBER	M	ENG VEL	RADIAL DISTORT.	CIRCUM. DISTORT.	K <sub>D</sub>	AUG. RATIO
1342.113222	0.615	95.141	0.0033 SAT	0.0430UNSAT	1.2081	0.0
1352.112333	0.656	101.413	0.0022 SAT	0.0428UNSAT	0.8028	0.0
1413.113222	0.655	101.255	0.0014 SAT	0.0429UNSAT	0.9861	0.0
1413.113223	0.521	80.569	0.0016 SAT	0.0427 SAT	0.3397	0.0
1413.213222	0.662	102.330	0.0026 SAT	0.0430UNSAT	0.8710	0.0
1413.313222	0.670	103.497	0.0025 SAT	0.0428 SAT	0.7493	0.0
1413.413142	0.516	79.737	0.0023 SAT	0.0397 SAT	0.4257	0.0
1413.413222	0.685	105.908	0.0019 SAT	0.0427 SAT	0.5130	0.0
1413.413223	0.518	80.071	0.0019 SAT	0.0397 SAT	0.2691	0.0
1421.113222	0.664	102.611	0.0012 SAT	0.0430UNSAT	1.3696	0.0
1421.213222	0.662	102.262	0.0017 SAT	0.0398 SAT	0.8665	0.0
1421.313222	0.665	102.772	0.0017 SAT	0.0428UNSAT	0.6173	0.0
1421.413142	0.511	79.058	0.0021 SAT	0.0397 SAT	0.2415	0.0
1421.413222	0.673	104.047	0.0016 SAT	0.0427 SAT	0.6543	0.0
1421.413223	0.519	80.191	0.0011 SAT	0.0397 SAT	0.1923	0.0
1421.413543	0.469	72.583	0.0027 SAT	0.0443UNSAT	1.8047	4.251
1422.112222	0.660	101.964	0.0019 SAT	0.0398 SAT	0.9058	0.0
1422.113222	0.651	100.589	0.0002 SAT	0.0399 SAT	0.9688	0.0
1431.113222	0.683	105.519	0.0015 SAT	0.0428UNSAT	1.1575	0.0
1431.113223	0.525	81.091	0.0003 SAT	0.0433UNSAT	0.8157	0.0
1431.213142	0.512	79.193	0.0024 SAT	0.0400 SAT	0.6932	0.0
1431.213222	0.660	102.006	0.0015 SAT	0.0429UNSAT	0.8362	0.0
1431.213442	0.430	66.593	0.0041UNSAT	0.0435UNSAT	0.7998	3.797





CONFIG NUMBER	M	ENG VEL	RADIAL DISTORT.	CIRCUM- DISTORT.	K <sub>D</sub>	AUG. RATIO
1431.213543	0.439	67.919	0.0036 SAT	0.0436UNSAT	1.5928	4.593
1431.313222	0.662	102.262	0.0025 SAT	0.0428UNSAT	0.7317	0.0
1431.413222	0.672	103.867	0.0015 SAT	0.0428UNSAT	0.5632	0.0
1431.413223	0.519	80.277	0.0014 SAT	0.0427 SAT	0.2674	0.0
1432.113222	0.666	132.881	0.0024 SAT	0.0428UNSAT	0.6691	0.0
1432.113223	0.521	80.516	0.0014 SAT	0.0397 SAT	0.2839	0.0
1432.313222	0.663	102.476	0.0034 SAT	0.0428UNSAT	0.5861	0.0
1432.413222	0.658	131.728	0.0023 SAT	0.0398 SAT	1.2544	0.0
1432.413223	0.519	80.237	0.0011 SAT	0.0397 SAT	0.2605	0.0
1432.513222	0.655	131.213	0.0019 SAT	0.0427 SAT	0.8127	0.0
1441.113142	0.486	75.162	0.0034 SAT	0.0437UNSAT	2.2344	0.0
1441.213222	0.601	92.899	0.0032 SAT	0.0435UNSAT	2.3310	0.0
1441.213223	0.497	76.892	0.0011 SAT	0.0433UNSAT	0.8497	0.0
1441.313222	0.602	93.129	0.0030 SAT	0.0430UNSAT	1.0353	0.0
1441.413222	0.613	94.692	0.0029 SAT	0.0429UNSAT	0.8877	0.0
1441.513222	0.598	92.468	0.0014 SAT	0.0436UNSAT	1.9607	0.0
1442.113222	0.590	91.242	0.0023 SAT	0.0407 SAT	1.5301	0.0
1445.113222	0.593	91.732	0.0026 SAT	0.0430UNSAT	1.4029	0.0
1452.113222	0.653	100.938	0.0023 SAT	0.0399 SAT	0.7254	0.0
1513.113222	0.660	102.011	0.0014 SAT	0.0397 SAT	0.8318	0.0
1513.413222	0.689	106.546	0.0014 SAT	0.0426 SAT	0.3537	0.0
1513.413543	0.478	73.945	0.0042UNSAT	0.0436UNSAT	1.7761	3.761
1521.413222	0.674	134.185	0.0010 SAT	0.0427 SAT	0.3770	0.0



CONFIG NUMBER	M	ENG VEL	RADIAL DISTORT.	CIRCUM- DISTORT.	K <sub>D</sub>	AUG- RATIO
1531.113223	0.530	81.903	0.0010 SAT	0.0427 SAT	0.3465	0.0
5114.413222	0.660	101.985	0.0021 SAT	0.0432UNSAT	2.3709	0.0
1531.413222	0.673	104.078	0.0022 SAT	0.0427 SAT	0.3536	0.0
1532.113222	0.668	103.239	0.0044UNSAT	0.0429UNSAT	1.1711	0.0
1542.113222	0.597	92.416	0.0042UNSAT	0.0408 SAT	2.4297	0.0
2113.113222	0.666	103.006	0.0009 SAT	0.0426 SAT	3.3637	0.0
2113.173222	0.662	102.304	0.0013 SAT	0.0401 SAT	1.2379	0.0
2122.113222	0.658	101.755	0.0009 SAT	0.0396 SAT	0.2661	0.0
2132.113222	0.662	102.283	0.0026 SAT	0.0427 SAT	3.7569	0.0
2142.113222	0.607	93.797	0.0037UNSAT	0.0401 SAT	1.2660	0.0
2152.113222	0.660	101.980	0.0011 SAT	0.0428UNSAT	0.4849	0.0
3113.112122	0.930	144.040	0.0466UNSAT	0.0399 SAT	2.2277	0.0
3113.113122	0.671	103.692	0.0003 SAT	0.0396 SAT	0.2617	0.0
4113.213222	0.669	103.453	0.0029 SAT	0.0429UNSAT	1.5388	0.0
4113.313222	0.668	103.244	0.0034 SAT	0.0399 SAT	0.6376	0.0
4132.113222	0.661	102.231	0.0025 SAT	0.0427 SAT	0.5840	0.0
4132.413222	0.661	102.111	0.0021 SAT	0.0427 SAT	0.6446	3.0
5113.113142	0.514	79.408	0.0034 SAT	0.0434UNSAT	1.1222	0.0
5113.113222	0.659	101.933	0.0044UNSAT	0.0431UNSAT	1.4012	0.0
5113.113223	0.524	81.025	0.0010 SAT	0.0433UNSAT	1.3176	0.0
5113.213222	0.666	102.892	0.0020 SAT	0.0430UNSAT	1.3761	0.0
5113.213223	0.518	80.031	0.0015 SAT	0.0434UNSAT	1.1849	0.0
5113.413222	0.662	102.288	0.0028 SAT	0.0433UNSAT	1.7652	0.0



CONFIG NUMBER	M	ENG VEL	RADIAL DISTORT.	CIRCUM. DISTORT.	K D	AUG. RATIO
5113.413223	0.520	80.397	0.0025 SAT	0.0432UNSAT	1.3538	0.0
5114.413223	0.523	80.867	0.0029 SAT	0.0435UNSAT	1.2837	0.0
5121.113632	0.500	77.269	0.0020 SAT	0.0398 SAT	3.2818	3.0
5121.713632	0.503	77.820	0.0015 SAT	0.0428UNSAT	0.6193	0.0
5121.813632	0.505	78.080	0.0031 SAT	0.0429UNSAT	3.5982	0.0
5121.913632	0.501	77.497	0.0021 SAT	0.0429UNSAT	0.8172	0.0
5124.113222	0.653	101.023	0.0026 SAT	0.0432UNSAT	1.9421	0.0
5124.113223	0.519	80.271	0.0029 SAT	0.0432UNSAT	1.3354	3.0
5124.213222	0.652	100.827	0.0047UNSAT	0.0432UNSAT	1.6720	0.0
5124.213223	0.515	79.657	0.0023 SAT	0.0430UNSAT	0.8582	0.0
5124.413142	0.513	79.381	0.0046UNSAT	0.0436UNSAT	1.4810	0.0
5124.413222	0.655	101.282	0.0017 SAT	0.0432UNSAT	1.8122	0.0
5124.413223	0.521	80.576	0.0027 SAT	0.0432UNSAT	1.2253	3.0
5124.413442	0.395	61.407	0.0047UNSAT	0.0453UNSAT	2.8919	3.770
5124.513442	0.373	58.359	0.0069UNSAT	0.0483UNSAT	5.1863	3.647
5131.113632	0.507	78.387	0.0024 SAT	0.0399 SAT	0.5632	3.0
5131.713632	0.503	77.772	0.0020 SAT	0.0430UNSAT	0.8742	0.0
5131.813632	0.506	78.162	0.0025 SAT	0.0399 SAT	3.6508	0.0
5131.913632	0.501	77.483	0.0025 SAT	0.0402 SAT	1.1054	0.0
5132.413542	0.371	57.484	0.0046UNSAT	0.0444UNSAT	1.0127	6.376
5132.713342	0.477	73.793	0.0043UNSAT	0.0428UNSAT	3.6498	3.493
5134.113222	0.658	101.718	0.0029 SAT	0.0431UNSAT	1.8226	0.0



CONFIG NUMBER	M	ENG VEL	RADIAL DISTORT.	CIRCUM- DISTORT.	K D	AUG. RATIO
5134.113223	0.513	79.341	0.0038UNSAT	0.0432UNSAT	0.8659	0.0
5134.213222	0.651	100.700	0.0031 SAT	0.0431UNSAT	1.6724	0.0
5134.213223	0.511	79.045	0.0006 SAT	0.0403 SAT	1.1970	0.0
5134.213442	0.367	56.812	0.0054UNSAT	0.0439UNSAT	1.5316	3.844
5134.513442	0.441	76.694	0.0512UNSAT	0.0597UNSAT	18.5831	3.074





DATA SUMMARY  
ORDERED BY DISTORTION LEVEL

CONFIG NUMBER	M	ENG VEL	RADIAL DISTORT.	CIRCUM- DISTORT.	K D	AUG. RATIO
3113.113122	0.671	102.692	0.0003 SAT	0.0396 SAT	0.2617	0.0
2122.113222	0.658	101.755	0.0009 SAT	0.0396 SAT	0.2661	0.0
1222.112222	0.669	103.435	0.0014 SAT	0.0396 SAT	0.4508	0.0
1131.413223	0.519	80.297	0.0009 SAT	0.0397 SAT	0.2334	0.0
1421.413223	0.519	80.191	0.0011 SAT	0.0397 SAT	0.1933	0.0
1221.413222	0.679	104.966	0.0009 SAT	0.0397 SAT	0.4455	0.0
1421.413142	0.511	79.058	0.0021 SAT	0.0397 SAT	0.2415	0.0
1331.413222	0.674	104.124	0.0007 SAT	0.0397 SAT	0.7611	0.0
1432.113223	0.521	80.516	0.0014 SAT	0.0397 SAT	0.2839	0.0
1122.112222	0.665	102.840	0.0006 SAT	0.0397 SAT	0.6558	0.0
1231.413222	0.677	104.620	0.0009 SAT	0.0397 SAT	0.6090	0.0
1113.413222	0.691	106.846	0.0012 SAT	0.0397 SAT	0.4010	0.0
1121.413222	0.680	105.098	0.0016 SAT	0.0397 SAT	0.5731	0.0
1432.413223	0.519	80.237	0.0011 SAT	0.0397 SAT	0.2605	0.0
1513.113222	0.660	102.011	0.0014 SAT	0.0397 SAT	0.8318	0.0
1252.113222	0.660	102.085	0.0010 SAT	0.0398 SAT	0.5323	0.0



CONFIG NUMBER	M	ENG VEL	RADIAL DISTORT.	CIRCUM- DISTORT.	K <sub>D</sub>	AUG. RATIO
1232.413223	0.532	82.208	0.0016 SAT	0.0397 SAT	0.3593	0.0
1313.413222	0.664	102.606	0.0017 SAT	0.0397 SAT	0.4789	0.0
1313.313222	0.670	103.626	0.0017 SAT	0.0398 SAT	0.6598	0.0
1413.413223	0.518	83.071	0.0019 SAT	0.0397 SAT	0.2691	0.0
1413.413142	0.516	79.737	0.0023 SAT	0.0397 SAT	0.4257	0.0
5121.113632	0.500	77.269	0.0020 SAT	0.0398 SAT	0.2818	0.0
1421.213222	0.662	102.262	0.0017 SAT	0.0398 SAT	0.8665	0.0
1422.112222	0.660	101.964	0.0019 SAT	0.0398 SAT	0.9058	0.0
1213.413543	0.501	77.469	0.0010 SAT	0.0398 SAT	0.4407	3.588
1432.413222	0.658	101.728	0.0023 SAT	0.0398 SAT	1.2544	0.0
1221.113142	0.521	80.476	0.0008 SAT	0.0399 SAT	0.6512	0.0
1213.413142	0.585	90.443	0.0008 SAT	0.0398 SAT	0.6386	0.0
4113.313222	0.668	103.244	0.0034 SAT	0.0399 SAT	0.6376	0.0
3113.112122	0.930	144.040	0.0466UNSAT	0.0399 SAT	2.2277	0.0
1422.113222	0.651	100.589	0.0002 SAT	0.0399 SAT	0.9688	0.0
1121.113222	0.672	103.883	0.0006 SAT	0.0399 SAT	1.1141	0.0
5131.113632	0.507	78.387	0.0024 SAT	0.0399 SAT	0.5632	0.0
1231.113222	0.651	100.653	0.0006 SAT	0.0399 SAT	0.7639	0.0
1221.113222	0.670	103.574	0.0006 SAT	0.0399 SAT	0.7268	0.0
1452.113222	0.653	100.938	0.0023 SAT	0.0399 SAT	0.7254	0.0
5131.813632	0.506	78.162	0.0025 SAT	0.0399 SAT	0.6508	0.0
1231.113223	0.535	82.778	0.0005 SAT	0.0400 SAT	0.5463	0.0
1431.213142	0.512	79.193	0.0024 SAT	0.0400 SAT	0.6932	0.0



CONFIG NUMBER	M	ENG VEL	RADIAL DISTORT.	CIRCUM- DISTORT.	K <sub>D</sub>	AUG. RATIO
1131.113222	0.651	100.642	0.0012 SAT	0.0400 SAT	0.6798	0.0
1222.313142	3.490	75.805	0.0019 SAT	0.0400 SAT	0.6445	0.0
1321.313222	0.666	102.990	0.0021 SAT	0.0400 SAT	1.2651	0.0
2113.173222	0.662	102.304	0.0013 SAT	0.0401 SAT	1.2379	0.0
1322.313542	0.445	68.824	0.0047UNSAT	0.0401 SAT	3.7936	3.234
1321.113222	0.663	102.559	0.0026 SAT	0.0401 SAT	1.1816	0.0
2142.113222	0.607	93.797	0.0037UNSAT	0.0401 SAT	1.2660	0.0
1341.113142	0.485	74.948	0.0026 SAT	0.0401 SAT	0.7744	0.0
1313.413543	0.461	74.334	0.0036UNSAT	0.0401 SAT	0.6303	3.740
5131.913632	0.501	77.483	0.0025 SAT	0.0402 SAT	1.1054	0.0
1322.313142	0.499	77.207	0.0027 SAT	0.0402 SAT	0.5707	0.0
5134.213223	0.511	79.045	0.0006 SAT	0.0403 SAT	1.1970	0.0
1142.113222	0.592	91.516	0.0022 SAT	0.0405 SAT	1.2020	0.0
1245.113222	0.590	91.289	0.0023 SAT	0.0405 SAT	1.5154	0.0
1242.113222	0.588	90.914	0.0029 SAT	0.0406 SAT	1.5013	0.0
1442.113222	0.590	91.242	0.0023 SAT	0.0407 SAT	1.5301	0.0
1542.113222	0.597	92.416	0.0042UNSAT	0.0408 SAT	2.4297	0.0
2113.113222	0.666	103.006	0.0009 SAT	0.0426 SAT	3.3637	0.0
1513.413222	0.689	106.546	0.0014 SAT	0.0426 SAT	0.3537	0.0
1222.113222	0.660	102.017	0.0008 SAT	0.0426 SAT	0.2627	0.0
1113.313222	0.673	104.047	0.0011 SAT	0.0427 SAT	0.2608	0.0
1213.413222	0.669	103.394	0.0013 SAT	0.0426 SAT	0.4594	0.0
1232.313222	0.669	103.388	0.0015 SAT	0.0427 SAT	0.5738	0.0



CONFIG NUMBER	M	ENG VEL	RADIAL DISTORT.	CIRCUM- DISTORT.	K <sub>D</sub>	AUG. RATIO
1332.413222	0.661	102.116	0.0020 SAT	0.0427 SAT	0.4180	0.0
1113.413222	0.667	103.068	0.0008 SAT	0.0427 SAT	0.3635	0.0
1231.313222	0.671	103.708	0.0009 SAT	0.0427 SAT	0.6156	0.0
1521.413222	0.674	104.185	0.0010 SAT	0.0427 SAT	0.3770	0.0
1531.113223	0.530	81.903	0.0010 SAT	0.0427 SAT	0.3465	0.0
1531.413222	0.673	104.078	0.0022 SAT	0.0427 SAT	0.3536	0.0
1331.313222	0.662	102.283	0.0016 SAT	0.0427 SAT	0.8257	0.0
1413.113223	0.521	80.569	0.0016 SAT	0.0427 SAT	0.3397	0.0
1232.513222	0.665	102.793	0.0017 SAT	0.0427 SAT	0.7684	0.0
1132.113222	0.673	104.042	0.0017 SAT	0.0427 SAT	0.4863	0.0
1232.413222	0.665	102.731	0.0022 SAT	0.0427 SAT	0.5294	0.0
4132.413222	0.601	102.111	0.0021 SAT	0.0427 SAT	0.6446	0.0
1231.213222	0.668	103.208	0.0013 SAT	0.0427 SAT	0.5839	0.0
1413.413222	0.685	105.908	0.0019 SAT	0.0427 SAT	0.5130	0.0
1432.513222	0.655	101.213	0.0019 SAT	0.0427 SAT	0.8127	0.0
2132.113222	0.662	102.283	0.0026 SAT	0.0427 SAT	0.7569	0.0
1331.113222	0.647	100.030	0.0015 SAT	0.0427 SAT	0.8420	0.0
1213.413223	0.522	80.649	0.0015 SAT	0.0427 SAT	0.2015	0.0
1421.413222	0.673	104.047	0.0016 SAT	0.0427 SAT	0.6543	0.0
4132.113222	0.601	102.231	0.0025 SAT	0.0427 SAT	0.5840	0.0
1431.413223	0.519	80.277	0.0014 SAT	0.0427 SAT	0.2674	0.0
1232.113222	0.676	104.482	0.0017 SAT	0.0427 SAT	0.6962	0.0
1221.213222	0.667	103.083	0.0020 SAT	0.0427 SAT	0.6362	0.0





CONFIG NUMBER	M	ENG VEL	RADIAL DISTORT.	CIRCUM. DISTORT.	K D	AUG. RATIO
1132.413222	0.662	102.366	0.0022 SAT	0.0427 SAT	0.7981	0.0
1232.113223	0.526	81.275	0.0013 SAT	0.0428 SAT	0.5152	0.0
1213.113223	0.523	80.814	0.0017 SAT	0.0428 SAT	0.2303	0.0
1131.313222	0.666	103.311	0.0020 SAT	0.0428 SAT	0.8638	0.0
1213.313222	0.676	104.564	0.0021 SAT	0.0428 SAT	0.7643	0.0
1413.313222	0.670	103.497	0.0025 SAT	0.0428 SAT	0.7493	0.0
1131.413222	0.675	104.380	0.0012 SAT	0.0428UNSAT	0.5851	0.0
1131.213222	0.665	102.824	0.0013 SAT	0.0428UNSAT	0.6107	0.0
1431.313222	0.662	102.262	0.0025 SAT	0.0428UNSAT	0.7317	0.0
1332.113222	0.670	103.538	0.0027 SAT	0.0428UNSAT	1.1801	0.0
1432.313222	0.663	102.476	0.0034 SAT	0.0428UNSAT	0.5861	0.0
1121.313222	0.672	103.800	0.0006 SAT	0.0428UNSAT	0.7879	0.0
1152.113222	0.660	102.017	0.0012 SAT	0.0428UNSAT	0.7284	0.0
1431.413222	0.672	103.867	0.0015 SAT	0.0428UNSAT	0.5632	0.0
1321.413222	0.676	104.553	0.0020 SAT	0.0428UNSAT	0.7551	0.0
1432.113222	0.666	102.881	0.0024 SAT	0.0428UNSAT	0.6691	0.0
5132.713342	0.477	73.793	0.0040UNSAT	0.0428UNSAT	0.6498	3.493
1213.113222	0.664	102.559	0.0005 SAT	0.0428UNSAT	0.7936	0.0
1113.213111	0.669	103.373	0.0017 SAT	0.0428UNSAT	0.4761	0.0
1213.213222	0.672	103.857	0.0017 SAT	0.0428UNSAT	0.8828	0.0
1213.413142	0.511	79.051	0.0019 SAT	0.0428UNSAT	0.7996	0.0
1352.112333	0.656	101.413	0.0022 SAT	0.0428UNSAT	0.8028	0.0
1113.113222	0.659	101.860	0.0007 SAT	0.0428UNSAT	0.9248	0.0



CONFIG NUMBER	N	ENG VEL	RADIAL DISTORT.	CIRCUM. DISTORT.	K D	AUG. RATIO
1421.313222	0.635	102.772	0.0017 SAT	0.0428UNSAT	0.6173	0.0
1221.313222	3.674	104.160	0.0003 SAT	0.0428UNSAT	1.3878	0.0
2152.113222	0.660	101.980	0.0011 SAT	0.0428UNSAT	0.4849	0.0
5121.713632	0.503	77.820	0.0015 SAT	0.0428UNSAT	0.6193	0.0
1321.413223	0.519	80.297	0.0016 SAT	0.0428UNSAT	3.7567	0.0
1231.113222	0.686	106.008	0.0000 SAT	0.0429UNSAT	1.2759	0.0
1431.113222	0.683	105.519	0.0015 SAT	0.0428UNSAT	1.1575	0.0
5121.913632	0.501	77.497	0.0021 SAT	0.0429UNSAT	0.8172	3.3
1413.113222	0.655	101.255	0.0014 SAT	0.0429UNSAT	0.9861	0.0
1431.213222	0.660	102.006	0.0015 SAT	0.0429UNSAT	3.8362	0.0
4113.213222	0.669	103.450	0.0029 SAT	0.0429UNSAT	1.5388	0.0
1532.113222	0.668	103.239	0.0044UNSAT	0.0429UNSAT	1.1711	0.0
1441.413222	0.613	94.692	0.0029 SAT	0.0429UNSAT	0.8877	3.0
5121.813632	0.505	78.080	0.0031 SAT	0.0429UNSAT	0.5982	0.0
1141.413222	0.615	95.102	0.0040UNSAT	0.0429UNSAT	0.9320	0.0
1131.113223	0.517	79.938	0.0013 SAT	0.0429UNSAT	0.6386	0.0
1213.213223	0.519	80.217	0.0009 SAT	0.0430UNSAT	0.5880	0.0
1421.113222	0.664	102.611	0.0012 SAT	0.0430UNSAT	1.3696	0.3
5113.213222	0.666	102.892	0.0020 SAT	0.0430UNSAT	1.3761	0.0
1445.113222	0.593	91.732	0.0026 SAT	0.0430UNSAT	1.4029	0.0
1441.313222	0.602	93.129	0.0030 SAT	0.0430UNSAT	1.0353	0.0
1241.413222	0.613	94.697	0.0053UNSAT	0.0429UNSAT	1.1393	0.0
1341.213222	0.606	93.620	0.0045UNSAT	0.0430UNSAT	1.2245	0.3



CONFIG NUMBER	M	ENG VEL	RADIAL DISTORT.	CIRCUM- DISTORT.	K <sub>D</sub>	AUG. RATIO
5131.713632	0.503	77.772	0.0020 SAT	0.0433UNSAT	0.8742	0.0
1321.213222	0.667	103.109	0.0024 SAT	0.0430UNSAT	1.2132	0.0
1121.213222	0.665	102.835	0.0031 SAT	0.0430UNSAT	0.9334	0.0
1341.413222	0.610	94.291	0.0041UNSAT	0.0430UNSAT	1.1878	0.0
1321.113142	0.519	80.231	0.0011 SAT	0.0430UNSAT	0.9013	0.0
1431.113223	0.525	81.091	0.0033 SAT	0.0433UNSAT	0.8157	0.0
1113.213223	0.518	80.038	0.0017 SAT	0.0430UNSAT	0.9272	0.0
5124.213223	0.515	79.657	0.0023 SAT	0.0430UNSAT	0.8582	0.0
1342.113222	0.615	95.141	0.0033 SAT	0.0430UNSAT	1.2081	0.0
1441.213223	0.497	76.882	0.0011 SAT	0.0430UNSAT	0.8497	0.0
1413.213222	0.662	102.330	0.0026 SAT	0.0433UNSAT	0.8710	0.0
1145.113222	0.593	91.633	0.0025 SAT	0.0431UNSAT	1.5177	0.0
1321.413142	0.511	78.997	0.0027 SAT	0.0431UNSAT	0.9284	0.0
5113.113222	0.659	101.933	0.0044UNSAT	0.0431UNSAT	1.4012	0.0
5134.213222	0.651	100.700	0.0031 SAT	0.0431UNSAT	1.6724	0.0
5134.113222	0.658	101.718	0.0029 SAT	0.0431UNSAT	1.8226	0.0
1141.313222	0.606	93.694	0.0036UNSAT	0.0431UNSAT	0.9948	0.0
1313.113222	0.654	101.076	0.0009 SAT	0.0431UNSAT	1.4935	0.0
1213.213142	0.518	80.091	0.0012 SAT	0.0432UNSAT	0.8522	0.0
5124.413222	0.655	101.282	0.0017 SAT	0.0432UNSAT	1.8122	0.0
5124.113222	0.653	101.023	0.0026 SAT	0.0432UNSAT	1.9421	0.0
5124.413223	0.521	80.576	0.0027 SAT	0.0432UNSAT	1.2253	0.0
1341.313222	0.606	93.626	0.0030 SAT	0.0431UNSAT	1.2006	0.0



CONFIG NUMBER	M	ENG VEL	RADIAL DISTORT.	CIRCUM. DISTORT.	K D	AUG. RATIO
1141.213222	0.610	94.279	0.0048UNSAT	0.0432UNSAT	1.5663	0.0
5124.113223	0.519	80.271	0.0029 SAT	0.0432UNSAT	1.3354	0.0
5134.113223	0.513	79.341	0.0038UNSAT	0.0432UNSAT	0.8659	0.0
1331.113223	0.529	81.753	0.0005 SAT	0.0432UNSAT	0.9666	0.0
1113.413543	0.495	76.478	0.0019 SAT	0.0432UNSAT	1.5234	3.635
1241.513222	0.616	95.226	0.0015 SAT	0.0432UNSAT	1.7527	0.0
5114.413222	0.650	101.985	0.0021 SAT	0.0432UNSAT	2.3709	0.0
5113.413223	0.520	80.397	0.0025 SAT	0.0432UNSAT	1.3538	0.0
5124.213222	0.652	100.827	0.0047UNSAT	0.0432UNSAT	1.6720	0.0
1313.213222	0.657	103.192	0.0022 SAT	0.0433UNSAT	1.3662	0.0
5113.113223	0.524	81.025	0.0010 SAT	0.0433UNSAT	1.3176	0.0
5113.413222	0.662	102.288	0.0028 SAT	0.0433UNSAT	1.7652	0.0
1141.213223	0.489	75.636	0.0011 SAT	0.0434UNSAT	0.8138	0.0
5113.113142	0.514	79.408	0.0034 SAT	0.0434UNSAT	1.1222	0.0
5113.213223	0.518	80.031	0.0015 SAT	0.0434UNSAT	1.1849	3.0
1441.213222	0.601	92.899	0.0032 SAT	0.0435UNSAT	2.3310	0.0
1213.313342	0.501	77.456	0.0019 SAT	0.0435UNSAT	1.6468	5.380
5114.413223	0.525	80.867	0.0029 SAT	0.0435UNSAT	1.2837	0.0
1121.313342	0.489	75.664	0.0042UNSAT	0.0435UNSAT	1.0884	1.425
1121.213342	0.492	76.044	0.0037UNSAT	0.0435UNSAT	2.0933	1.210
1431.213442	0.430	66.593	0.0041UNSAT	0.0435UNSAT	0.7998	3.797
1221.213342	0.490	75.847	0.0035UNSAT	0.0436UNSAT	1.7254	1.213
5124.413142	0.513	79.381	0.0046UNSAT	0.0436UNSAT	1.4810	0.0





CONFIG NUMBER	M	ENG VEL	RADIAL DISTORT.	CIRCUM. DISTORT.	K <sub>D</sub>	AUG. RATIO
1441.513222	0.598	92.468	0.0014 SAT	0.0436UNSAT	1.9607	0.0
1431.213543	0.439	67.919	0.0036 SAT	0.0436UNSAT	1.5928	4.593
1513.413543	0.478	73.945	0.0042UNSAT	0.0436UNSAT	1.7761	3.761
1332.113542	0.465	71.940	0.0044UNSAT	0.0436UNSAT	1.4225	3.001
1222.313542	0.461	71.367	0.0055UNSAT	0.0437UNSAT	1.4443	3.120
1441.113142	0.486	75.162	0.0034 SAT	0.0437UNSAT	2.2344	0.0
1121.113342	0.493	76.219	0.0048UNSAT	0.0437UNSAT	1.8473	1.197
1221.313342	0.492	76.086	0.0032 SAT	0.0438UNSAT	1.6497	1.417
5134.213442	0.367	56.812	0.0054UNSAT	0.0439UNSAT	1.5316	3.844
1221.113342	0.491	76.016	0.0040UNSAT	0.0441UNSAT	1.9822	1.201
1321.413543	0.483	74.749	0.0040UNSAT	0.0441UNSAT	2.6631	4.125
1313.313342	0.458	70.841	0.0055UNSAT	0.0442UNSAT	1.3388	5.887
1421.413543	0.469	72.583	0.0027 SAT	0.0443UNSAT	1.8047	4.251
5132.413542	0.371	57.484	0.0046UNSAT	0.0444UNSAT	1.0127	6.376
1132.113542	0.477	73.851	0.0043UNSAT	0.0448UNSAT	2.0010	2.994
1222.113542	0.480	74.599	0.0075UNSAT	0.0453UNSAT	3.4913	2.871
5124.413442	0.395	61.407	0.0047UNSAT	0.0453UNSAT	2.8919	3.770
1213.113543	0.511	79.355	0.0067UNSAT	0.0456UNSAT	6.3772	3.542
1122.113542	0.473	73.467	0.0049UNSAT	0.0473UNSAT	5.9342	2.871
1131.213543	0.463	72.185	0.0056UNSAT	0.0479UNSAT	7.1440	4.374
5124.513442	0.373	58.359	0.0069UNSAT	0.0483UNSAT	5.1863	3.647
1331.213543	0.461	71.769	0.0032 SAT	0.0484UNSAT	7.8237	3.761
1131.213442	0.478	74.592	0.0058UNSAT	0.0488UNSAT	7.2430	3.419



CONFIG NUMBER	M	ENG VEL	RADIAL DISTORT.	CIRCUM. DISTORT.	K D	AUG. RATIO
1331.213442	0.485	75.678	0.0072UNSAT	0.0488UNSAT	8.1328	3.367
1341.113543	0.131	21.323	0.0019 SAT	0.0590UNSAT	1.2712	8.303
5134.513442	0.441	76.694	0.0512UNSAT	0.0597UNSAT	18.5831	3.074



```

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# PROCESSING OF VERTICAL INLET VELOCITY SURVEY FOR TOTAL VOLUMETRIC FLOW RATE

RESERVE THE REQUIRED ARRAY AREAS

```

DIMENSION P(2,27),W(26),AREA(27),AP(1,27),PTEMP(1,26),TOTAR(27)

```

READ THE TEST DATA

```

60 READ(5,1000) CONFIG
1000 FORMAT(F12.6)
IF(CONFIG.LT.0.0) GO TO 50
DO 10 I=1,2
DO 11 J=2,26
1001 FORMAT(F12.4)
READ(5,1001) P(I,J)
11 CONTINUE
10 CONTINUE

```

INITIALIZE THE REQUIRED CONSTANTS

```

AY=0.1
W(1)=1.0/16.0
W(26)=W(1)
W(2)=7.0/16.0

```



```

W(25)=W(2)
DO 13 IJ=3,24
  W(IJ)=0.5000
13 CONTINUE

SET THE VELOCITY TO ZERO AT EACH WALL

DATA P(1,1),P(2,1),P(2,27), P(1,27)/4*0.0/

DETERMINE THE STATIC PRESSURE AT THE INTERSECTION OF THE
TRACES, BY AVERAGING THE FOUR SURROUNDING DATA POINTS

18 CONTINUE
AVG1=(P(1,10)+P(1,11))/2.0
AVG2=(P(2,10)+P(2,11))/2.0
AY=AY+1.0
AVG=(AVG1+AVG2)/2.0

REPORT THIS AVERAGE

22 FORMAT( '///F10.5,' INTERSECTION AVERAGE ')
WRITE(6,22)AVG

AREA(1)=0.0
AREA(27)=0.0
DO 14 L=2,26

ADJUST THE REPORTED PRESSURE AT EACH POINT ON THE TRACE BY
THE DIFFERENCE BETWEEN THE INTERSECTION AVERAGE AND THE
SECOND TRACE DATA POINT; DO THIS FOR EACH OF THE NON ZERO
POINTS ON THE SECOND TRACE

FACTOR=P(2,L)-AVG
AREA(L)=0.0
AP(1,1)=0.0
AP(1,27)=0.0

```





COMPUTE THE AREA UNDER THE ADJUSTED PRESSURE PROFILE  
 BETWEEN EACH PAIR OF DATA POINTS BY AVERAGING THESE POINTS  
 AND WEIGHTING THIS AVERAGE BY THE DISTANCE BETWEEN THEM  
 KEEP A RUNNING TOTAL OF THESE AREAS

```

DO 15 M=2,26
  AP(1,M)=P(1,M)+FACTOR
  AREA(M)=AREA(M-1)+(AP(1,M-1))+AP(1,M))/(2.0)*W(M-1)
  DATA TOTAR(1),TOTAR(27)/0.0,0.0/
15 CONTINUE

  TOTAR(L)=AREA(26)
23 FORMAT(10.5,' SLICE AREA ')
  WRITE(6,23)TOTAR(L)
14 CONTINUE

```

AFTER ALL SLICE AREAS ARE COMPUTED, AVERAGE EACH ADJACENT  
 PAIR OF SLICES AND WEIGHT THIS AVERAGE BY THEIR LATERAL  
 SEPARATION, KEEPING A RUNNING TOTAL OF THESE VOLUMES

```

VOL=0.0
DO 16 JK=2,27
  VOL=VOL+((TOTAR(JK-1)+TOTAR(JK))/(2.0))*W(JK-1)
16 CONTINUE

```

DIVIDE THE VOLUME TOTAL BY THE TOTAL FLOW AREA TO YIELD  
 THE AVERAGE DYNAMIC PRESSURE AND VOLUMETRIC FLOW RATE

```

PAVG=VOL/144.0
FLOW=66.119*(SQRT(PAVG))

```

PRINT OUT THESE RESULTS

```

20 FORMAT(//,' CONFIGURATION          Q ',
C, VOL, FLOW RATE,/ )
21 FORMAT(5X,F7.2,6X,F8.4,' IN H2O ',F9.4,' CFS ')
  WRITE(6,20)
  WRITE(6,21)CONFIG,PAVG,FLOW

```



REVERSE THE POSITIONS OF THE DATA TRACES IN STORAGE AND  
REPEAT THE COMPLETE AVERAGING PROCEDURE

```
DO 17 JL=2,26  
  PTEMP(1,JL)=P(1,JL)  
  P(1,JL)=P(2,JL)  
  P(2,JL)=PTEMP(1,JL)  
17 CONTINUE
```

IF ALL DATA SETS HAVE BEEN PROCESSED.....TERMINATE

```
IF (AY.LT.1.5) GO TO 18  
GOTO 80  
50 CONTINUE  
STOP  
END
```



# DISTORTION DATA PROCESSING

RESERVE THE REQUIRED STORAGE SPACE AND IDENTIFY THE  
VARIABLES WHICH REQUIRE DOUBLE PRECISION

```

DIMENSION BCON(10),SUBD(10),AUGRT(10)
DIMENSION PTOT(25),PSTAT(2),DGTL(25),PTSECT(8),DPC(TG(25),PTMWT(25)
C01SECT(8),PRING(3),CON(10),CMF(10),CVT(13),DIS(10),DFC(10),CONDC(1
C01XDBPM(3),BJK(3),ACDV(10)
REAL*8 DPRES,TWENTY,8NUM,BLIM,DFCIRM,CONFIG,CON

```

SET THE INPUT AND OUTPUT FORMATS

```

41 FORMAT(///,
42 FORMAT(///,
43 FORMAT(///,
45 FORMAT(//4X,13,4X,F7.4,2X,F7.4,2X,F6.4,9X,F8.4)
49 FORMAT(///,
51 FORMAT(///,
52 FORMAT(///,
53 FORMAT(///,
55 FORMAT(///,
56 FORMAT(///,
57 FORMAT(///,
59 FORMAT(///,

```

```

CONFIGURATION NUMBER ',F14.8)
THE COMPRESSOR FACE DATA
STATION PTOTAL PSTATIC MASS FLOW DISTORTION P
PERCENTAGE(//,
IN THE COMPUTED COEFFICIENTS FOR THIS RUN: ' ) ENGI
CNE MCOT
NUMERICAL AVG ', 2X,F8.4,7X,F8.4,10X,F8.4)
AREA WTD AVGS ', 2X,F8.4,7X,F8.4,13X,F8.4)
SECTOR ',13,
IN THE COMPUTATION OF THE CIRCUMFERENTIAL DISTORTI
CON INDEX THE AVERAGED SECTOR PRESSURES ARE REQUIRED: ' )
SECTOR ',14, IS CONSIDERED TO BE SPOILED ' )
THE AVERAGE TOTAL PRESSURE IN THESE SPOILED SECTORS

```









```

      IROUN=0
      IJK=1
99  CONTINUE
      READ(5,101) CONFIG,AUGAIR
      CON(IJK)=CONFIG

      IF NO MORE SETS FOLLOW PROCEED TO THE SUMMARY LIST

      IF(CONFIG.LT.0.0)GOTO 50
      IROUN=IROUN+1
      READ(5,103) PATM
      WPATM=PATM/0.073554

      CONVERT MANOMETER DISPLACEMENT DATA INTO ABSOLUTE
      PRESSURES

      DO 10 I=1,25
      READ(5,103) TOT
      PTOT(I)=WPATM-TOT
      CONTINUE
10  READ(5,103) IAT
      PSTAT(1)=WPATM-IAT
      READ(5,103) IAT
      PSTAT(2)=WPATM-IAT

      INITIALIZE THE REQUIRED INDICES, THEN LOCATE THE
      MAXIMUM AND MINIMUM TOTAL PRESSURE AND IDENTIFY
      THE LOCATION OF THESE READINGS

      DCN=0.0
      PTMAX=0.0
      PTMIN=1000.0
      DO 13 J=1,25
      DIFF=PTMAX-PTOT(J)
      IF(DIFF.LT.-0.005) GOTO 12
      GOTO 11
12  PTMAX=PTOT(J)
      INDEX=J
11  CONTINUE
      DIFFM=PTMIN-PTOT(J)

```



```

IF ( DIFFM.GT.0.005) GOTO 14
GOTO 13
PTMIN= PTOT(J)
INDEXM =J
13 CONTINUE
14
15

```

NUMERICALLY AVERAGE THE TOTAL PRESSURE DATA

```

SUM=0.0
DO 15 K=1,25
SUM= PTOT(K) + SUM
15 CONTINUE
PTAVG = SUM/25.0

```

AVERAGE THE TOTAL PRESSURE DATA BY AREA WEIGHTING  
THE RECORDED PRESSURES

```

ASUM=0.0
DO 16 L=1,8
ASUM = ASUM + (PTOT(L) * 0.596433 )
16 CONTINUE
ASUM2=0.0
DO 17 I1=9,16
ASUM2 = ASUM2 + (PTOT(I1) * 0.38935)
17 CONTINUE
ASUM3=0.0
DO 18 I1=17,24
ASUM3=ASUM3 + (PTOT(IJ) * 0.43997 )
18 CONTINUE
PTAAVG=(ASUM+ASUM2+ASUM3+(PTOT(25)*0.77309))/12.17911

```

AVERAGE THE STATIC PRESSURES

```

PSTAVG = (PSTAT(1) + PSTAT(2))/2.0

```

AVERAGE THE TOTAL PRESSURE DATA BY MASS FLOW  
WEIGHTING THE RECORDED PRESSURE USING THE NEAREST  
STATIC PROBE DATA OR THE AVERAGE OF THESE VALUES  
FOR THE NUMBER 25 (CENTER) PROBE



```

DO 19 JJ=1,3
VLOCAL=(SQRT(PTOT(JJ)-PSTAT(1)))*66.119
DOTL(JJ)=VLOCAL*0.596433*0.0765
CONTINUE
19 DO 20 JK=4,7
VLOCAL=(SQRT(PTOT(JK)-PSTAT(2)))*66.119
DOTL(JK)=VLOCAL*0.596433*0.0765
CONTINUE
20 DO 21 JM=9,11
VLOCAL=(SQRT(PTOT(JM)-PSTAT(1)))*66.119
DOTL(JM)=VLOCAL*0.38935*0.0765
CONTINUE
21 DO 22 JN=12,15
VLOCAL=(SQRT(PTOT(JN)-PSTAT(2)))*66.119
DOTL(JN)=VLOCAL*0.38935*0.0765
CONTINUE
22 DO 23 JO=17,19
VLOCAL=(SQRT(PTOT(JO)-PSTAT(1)))*66.119
DOTL(JO)=VLOCAL*0.43997*0.0765
CONTINUE
23 DO 24 JP=20,23
VLOCAL=(SQRT(PTOT(JP)-PSTAT(2)))*66.119
DOTL(JP)=VLOCAL*0.43997*0.0765
CONTINUE
24 DO 25 JQ=1,25
VLOCAL=(SQRT(PTOT(24)-PSTAT(1)))*66.119*0.43997*0.0765
DOTL(25)=(SQRT(PTOT(25)-PSTAT(1)))*66.119*0.77309*0.0765
DENOM=0.0
TOTAL=0.0
PTWTL(JQ)=PTOT(JQ)*DOTL(JQ)
TOTAL=TOTAL+PTWTL(JQ)
DENOM=DENOM+DOTL(JQ)
CONTINUE
25 PTMAVG=TOTAL/DENOM

```

USING THESE THREE AVERAGES, DETERMINE THE  
CORRESPONDING AVERAGE VELOCITIES AND MASS FLOW  
RATES

```

CMETR=DENOM/144.0
CVTRU=(SQRT(PTMAVG-PSTAVG))*66.119
CVTRU=SQRT(PTMAVG-PSTAVG)*66.119
CVEL=CVEL*(12.17911/144.0)*(0.0765)
CVEL=SQRT(PTAVG-PSTAVG)*66.119

```



CMDOT1=CVELL\*(12.17911/144.0)\*(0.0765)

DETERMINE THE MASS FLOW WEIGHTED AVERAGE TOTAL  
PRESSURE FOR EACH 45 DEGREE SECTOR

DO 26 JR=1,8  
PTSEC(JR)=(PTMWT(JR)+PTMWT(JR+8)+PTMWT(JR+16))/((DOTL(JR)+DOTL(JR+8)  
C)+DOTL(JR+16))  
26 CONTINUE

LOCATE THE MINIMUM SECTOR AVERAGE

ISUM=0  
PTSPL=1000.0  
DO 27 JS=1,8  
CG=PTSPL-PTSEC(JS)  
IF (CG.GE.0.0000) GOTO 28  
GO TO 27  
28 PTSPL=PTSEC(JS)  
INDK=JS  
27 CONTINUE

CHECK TO SEE IF THIS MINIMUM AVERAGE IS MORE THAN  
ONE PERCENT BELOW THE AVERAGE TOTAL PRESSURE

LX=1  
RADNUM=1.0  
DO 33 IKE=1,8  
SST=ABS(PTSEC(IKE)-PTSPL)  
IF (SST.GE.0.0005) GOTO 34  
33 CONTINUE  
GOTO 39  
34 CONTINUE

IF IT IS CONSIDER THIS SECTOR TO BE SPOILED AND  
EXAMINE THE ADJACENT SECTORS TO DETERMINE THE  
RADIAL EXTENT OF THE SPOILED AREA

LX=2  
INM=1





```

ISECT(1)=INDK
WAIT=(PTMAVG-PTSPL)/2.0
INDKT=INDK
35 FNDL=INDKT+INM
    IF(FNDL.GT.8.5) FNDL=FNDL-8.0
    IF(FNDL.LT.0.5) FNDL=FNDL+8.0
    INDL=FNDL
    GCS=ABS(PTSEC(INDL)-PTSPL)
    IF(GCS.LT.WAIT) GOTO 30
    GOTO 36
30 CONTINUE
    ISECT(LX)=INDL
    LX=LX+1
    RADNUM=RADNUM+1.0
    INDKT=FNDL
    GOTO 35
36 BOQ=INM
    IF(BOQ.GT.0.0) GOTO 37
    GOTO 38
37 INM=-1
    INDKT=INDK
    GOTO 35
38 CONTINUE

```

COMPUTE THE NAPTIC CIRCUMFERENTIAL DISTORTION FACTOR

```

DPRES=PTSPL-PSTAVG
TWENTY1=DSQRT(DPRES/PTSPL)
IF(RADNUM.LE.1.5) GOTO 244
BNUM=0.0425
GOTO 245
244 BNUM=0.0395
245 CONTINUE
39 DFCIRM=(BNUM)/(TWENTY1/(PTMAVG-PSTAVG)/PTMAVG)))
CONTINUE

```

CALCULATE THE STANDARD DISTORTION RATIOS

```

A=(PTMAX-PTMAVG)/PTMAVG
B=(PTMAVG-PTMIN)/PTMAVG
C=(PTMAX-PTMIN)/PTMAVG

```



DETERMINE THE MASS FLOW THRU EACH PROBE AREA AND THE  
PERCENTAGE DISTORTION OF THE VELOCITY PROFILE IN  
EACH ONE

```

DO 40 JU=1,25
  DPTG(JU)={ (PTOT(JU)/PTMAVG)-1.0 } * 100.0
  CONTINUE
DO 77 KQ=1,25
  DOTL(KQ)=DOTL(KQ)/144.0
  CONTINUE

```

FIND THE AVERAGE PRESSURE OF EACH PROBE RING

```

PRING(1)=0.0
PRING(2)=0.0
PRING(3)=0.0

```

FIND EQUAL FLOW RING DIMENSIONS AND DETERMINE THE  
AEDC DISTORTION FACTOR

```

DO 708 MM=1,3
  MQ={ (MM-1) * 8 } + 1
  MR=MQ+7
  PRIM(MM)=10000.0
  DO 707 MK=MQ,MR
    PRING(MM)=PRING(MM)+PTOT(MK)
  IF (PTOT(MK).LT.PRIM(MM)) GOTO 650

```

```

GOTO 651
650 PRIM(MM)=PTOT(MK)
651 CONTINUE
PRING(MM)=PRING(MM)/8.0

```

```

DO 652 JUL5=MQ,MR
  EL5=ABS(PTOT(JUL5)-PRIM(MM))
  IF (EL5.LE.WAIT) GOTO 653

```

```

GOTO 654
653 BJK(MM)=BJK(MM)+1.0
654 CONTINUE
652 CONTINUE
708 CRING1=2.0/0.65625
CRING2=2.0/1.3437

```



```

CRING3=2.0/1.6875
PNB=(({PRING(1)}-PRIM(1))/PRING(1))*({BJK(1)}*45.0)*CRING1
PNC=(({PRING(2)}-PRIM(2))/PRING(2))*({BJK(2)}*45.0)*CRING2
PND=(({PRING(3)}-PRIM(3))/PRING(3))*({BJK(3)}*45.0)*CRING3
AEDC=({100.0*({PNB+PNC+PND}))/CRING1+CRING2+CRING3}

```

EVALUATE THE NAPTIC RADIAL DISTORTION FACTOR

```

709 IF(PRING(1).LT.PRNG(2)) GOTO 709
    IF(PRING(2).LT.PRNG(3)) GOTO 710
    IF(PRING(1).LT.PRNG(3)) GOTO 711

```

```

    PRMIN=PRING(3)
    IEX=3
    ROI=11.0/16.0
    RBAR=1.0
    GOTO 712

```

```

710 PRMIN=PRING(2)
    IEX=2
    ROI=6.0/16.0
    RBAR=1.3750
    GOTO 712

```

```

711 PRMIN=PRING(1)
    IEX=1
    ROI=5.0/16.0
    RBAR=1.75

```

```

712 CONTINUE
    RADRAT=({RBAR*ROI})/(2.0/1.75)
    DISAMP=-((PRMIN-PTMAVG)/PTMAVG)*40.0
    IF(DISAMP.LE.0.0) DISAMP=0.0000

```

MAKE THE REQUIRED UNIT CONVERSIONS AND PRINT THE  
INDIVIDUAL PROBE AND AVERAGED VALUES

```

WRITE (6,41) CONFIG
WRITE (6,42)
WRITE (6,43)
AJJ=2.5

```

```

PSTAT(1)=PSTAT(1)*0.036126
PSTAT(2)=PSTAT(2)*0.036126

```



```

DO 44 JV=1,24
  PTOT(JV)=PTOT(JV)*0.036126
  WRITE(6,45) JV,PTOT(JV),PSTAT(JX), DOTL(JV),DPCTG(JV)
  COUNT=JV
  IF(COUNT.GT.AJJ) GOTO 46
  JX=1
  AJW=1.0
  GOTO 44
46  JX=2
    IF(AJW.GT.3.1) GOTO 47
    AJW=AJW+1.0
    GOTO 44
47  AJJ=AJJ+8.0
44  CONTINUE
  JV=25
  PSTAVG=PSTAVG*0.036126
  PTOT(25)=PTOT(25)*0.036126
  WRITE(6,45) JV,PTOT(JV),PSTAVG, DOTL(JV),DPCTG(JV)
  WRITE(6,1112)
  WRITE(6,49)
  WRITE(6,51)
  PTAVG=PTAVG*0.036126
  PTAAVG=PTAAVG*0.036126
  PTMVG=PTMVG*0.036126
  CMACH=SORI((2.0/0.4)*((PTMVG/PSTAVG)**(0.4/1.4))-1.0))
  WRITE(6,52) PTAVG,CVEL,CMDOI
  WRITE(6,53) PTAAVG,CVEL,CMDOI
  WRITE(6,151) PTMVG,CVTRU,CMFTR
  WRITE(6,1234) CMACH

```

C PRINT THE RESULTS OF THE SECTOR AVERAGE CALCULATIONS

```

WRITE(6,56)
DO 54 KR=1,8
  PTSEC(KR)=PTSEC(KR)*0.036126
  WRITE(6,55) KR,PTSEC(KR)
54  CONTINUE

```

IDENTIFY THE SPOILED SECTORS AND PRINT THE CIRCUM-  
FERENTIAL DISTORTION FACTOR WITH ITS EVALUATION AS  
TO SAT-UNSAT AND THE RPM LIMIT TO WHICH IT WOULD  
REMAIN SATISFACTORY

CLX=LX-1





```

IF (CLX,LT,0.5) GOTO 1110
LX=LX+1
ASSP=0.0
DO 58 KS=1,LX
WRITE(6,57) ISECT(KS)
KIS=ISECT(KS)
ASSP=ASSP+PTSEC(KIS)
CONTINUE
58 DAVS=LX
PTSPL=(ASSP/DAVS)
WRITE(6,59) PTSPL
WRITE(6,61) DFCIRM
IF (RADNUM.LE,1.5) GOTO 257
BLIM=0.04278
GOTO 258
257 BLIM=0.04250
258 CONTINUE
IF (DFCIRM.GT,.3LIM) GOTO 1020
SLRPM=11650.0+2504.0*(DFCIRM/0.0425)
WRITE(6,1001) SLRPM
GOTO 1002
CONTINUE
1110 DFCIRM=0.0000
WRITE(6,1099)
GOTO 1002
1020 WRITE(6,869)
DON=1.0
WRITE(6,1003)
CONTINUE
1002

```

EVALUATE THE RADIAL DISTORTION FACTOR AND OUTPUT ITS VALUE AND THE RESULTING CONDITION OF OPERATION

```

IF (RADRAT.GT,0.373) GOTO 850
CDIF=0.373-RADRAT
SLINE=0.055+(CDIF*.083333)
ADMAT=10.9
GOTO 851
850 CDIF=ADMAT-0.3730
SLINE=0.032+(CDIF*.0353)
ADMAT=0.0
CONTINUE
851 WRITE(6,860)
PRING(1)=PRING(1)*0.036126
PRING(2)=PRING(2)*0.036126
PRING(3)=PRING(3)*0.036126

```



```

WRITE(6,861) PRING(1),PRING(2),PRING(3)
WRITE(6,862) RADRAI,DISAMP
IF(DISAMP.GT.1.SLINE) GOTO 870
WRITE(6,872) SLINE
GOTO 883
CONTINUE
WRITE(6,869)
DON=1.0
WRITE(6,871) SLINE
IF(ADMAT.GT.5.5) GOTO 890
WRITE(6,892)
GOTO 891
WRITE(6,893)
CONTINUE
CONTINUE
870
890
891
880

```

# LIST THE OTHER DISTORTION FACTORS

```

WRITE(6,62) A,B,C
WRITE(6,678) AEDC
WRITE(6,63) PATM

```

## STORE SUMMARY DATA

```

CONDC(IJK)=DON
BCON(IJK)=BOON
SUBD(IJK)=AEDC
AUGRT(IJK)=AUGAIR/CMFTR
CMF(IJK)=CMFTR
CVT(IJK)=CVTRU
DIS(IJK)=DISAMP
DEC(IJK)=DECIPM
ACDV(IJK)=CVTRU*(12.17911/144.0)

```

WHEN THE LAST DATA SET HAS BEEN PROCESSED PRINT A SUMMARY TABLE OF THE RESULTS FOR EACH CONFIGURATION

```

IJK=IJK+1
DON=0.0
GOTO 99
CONTINUE
50
WRITE(6,299)
WRITE(6,300)

```



```

DO 66 IJK=1, IROUN
IF (BCON(IJK).GT.0.5) GOTO 9100
IF (CONDC(IJK).GT.0.5) GOTO 9093
GOTO 9090
9100 IF (CONDC(IJK).GT.0.5) GOTO 9092
GOTO 9091
9093 WRITE(6,301) CON(IJK),CMF(IJK),CVT(IJK),ACDV(IJK),DIS(IJK),DFC(IJK)
C),SUBD(IJK),AUGRT(IJK)
GOTO 66
9090 WRITE(6,302) CON(IJK),CMF(IJK),CVT(IJK),ACDV(IJK),DIS(IJK),DFC(IJK)
C),SUBD(IJK),AUGRT(IJK)
GOTO 66
9091 WRITE(6,303) CON(IJK),CMF(IJK),CVT(IJK),ACDV(IJK),DIS(IJK),DFC(IJK)
C),SUBD(IJK),AUGRT(IJK)
GOTO 66
9092 WRITE(6,304) CON(IJK),CMF(IJK),CVT(IJK),ACDV(IJK),DIS(IJK),DFC(IJK)
C),SUBD(IJK),AUGRT(IJK)
66 CONTINUE

```

```

STOP
END

```



PROGRAM TO SORT SUMMARY DATA  
BY CONFIGURATION CODE AND PRINT  
TABLES OF CONFIGURATIONS HAVING  
COMMON COMPONENTS

RESERVE THE REQUIRED STORAGE SPACE AND DESIGNATE  
THE DOUBLE PRECISION VARIABLES

```

DIMENSION CON(300), CMF(300), CVT(300), DIS(300), DFC(300), CONDC(300), 00000022
CACDV(300), SUBD(300), AUGRT(320), BCON(300), ZCVT(300), ZDIS(300), ZDFC(300), 00000030
C300), CONDC(300), ZACDV(300), ZSUBD(300), ZAUGRT(300), ZBCON(300), SUBL 00000040
CIS(300), ZCMF(300)
REAL*8 FCON, FCONDC, FSUBD, FCMF, FCVT, FDIS, FDFC, FACDV, FAUGRT, FBCON 00000060
REAL*8 RCON, CONHD 00000070
REAL*8 CON, SUBLIS, UPPER, LOWER 00000080

```

READ IN SUMMARY DATA LINES UNTIL A NEGATIVE  
CONFIGURATION IS ENCOUNTERED

```

DO 9301 I2=1,300
  READ (5,9302) CON(I2), CMF(I2), CVT(I2), ACDV(I2), DIS (I2)
  IF (CON(I2), LT, 0) GO TO 9973
  READ (5,9302) DFC(I2), SUBD(I2), AUGRT(I2), CONDC(I2), BCON(I2)
  CONTINUE
CONTINUE
9301
9973

```

SET THE REQUIRED INPUT AND OUTPUT FORMATS





```

9303 FORMAT(I6)
9302 FORMAT(5F12.6)
9303 FORMAT(5F12.6)
299 FORMAT(//,
CIAL LEVEL,
300 FORMAT(
CUTION
301 FORMAT(/,F12.6,F6.3,F8.3,F7.4,
302 FORMAT(/,F12.6,F6.3,F8.3,F7.4,
303 FORMAT(/,F12.6,F6.3,F8.3,F7.4,
304 FORMAT(/,F12.6,F6.3,F8.3,F7.4,
1100 FORMAT(F6.2,F6.2)
1104 FORMAT(IH1,/,/,/,
CDIGIT,

```

```

00000160
00000170
00000180
00000190
00000200
00000210
00000220

```

```

00000270

```

ESTABLISH A RETURN POINT AND SET COUNTING INDICES

```

11000150
11000160
11000170
11000180
11000190
11000200
11000210
11000220

```

COMPARE THE FIRST TWO CONFIGURATION CODES. IF THEY  
ARE IN ASCENDING ORDER COMPARE THE SECOND AND  
THIRD CODES. CONTINUE UNTIL A PAIR IS FOUND TO  
BE OUT OF ORDER

```

DO 500 I3=1,IROUND
IF(CON(I3).LE.CON(I3+1)) GOTO 502

```

TRANSFER THE FIRST UNORDERED SET TO TEMPORARY  
STORAGE

```

FCON=CON(I3)
FCNDC=CONDC(I3)
FSUBD=SUBD(I3)
FCMF=CMF(I3)
FCVT=CVT(I3)
FDIS=DIS(I3)
FDFC=DFC(I3)
FACDV=ACDV(I3)
FAUGRT=AUGRT(I3)
FBCON=BCON(I3)

```

```

00000330
00000340

```

```

00000350
00000360
00000370
00000380
00000390
00000400
00000410
00000420
00000430
00000440

```



REPLACE THE FIRST SET WITH THE SECOND

```
CON(I3)=CON(I3+1)
CONDC(I3)=CONDC(I3+1)
SUBD(I3)=SUBD(I3+1)
CMF(I3)=CMF(I3+1)
CVT(I3)=CVT(I3+1)
DIS(I3)=DIS(I3+1)
DFC(I3)=DFC(I3+1)
ACDV(I3)=ACDV(I3+1)
AUGRT(I3)=AUGRT(I3+1)
BCON(I3)=BCON(I3+1)
```

```
00000450
00000460
00000470
00000480
00000490
00000500
00000510
00000520
00000530
00000540
```

REPLACE THE SECOND DATA SET WITH THE FIRST FROM ITS  
TEMPORARY STORAGE LOCATION

```
CON(I3+1)=FCON
CONDC(I3+1)=FCONDC
SUBD(I3+1)=FSUBD
CMF(I3+1)=FCMF
CVT(I3+1)=FCVT
DIS(I3+1)=FDIS
DFC(I3+1)=FDFC
ACDV(I3+1)=FACDV
AUGRT(I3+1)=FAUGRT
BCON(I3+1)=FBCON
```

```
00000550
00000560
00000570
00000580
00000590
00000600
00000610
00000620
00000630
00000640
```

INDICATE THAT A CHANGE HAS BEEN MADE DURING THIS PASS

CHANGE=1.0  
502 CONTINUE

```
00000650
00000660
```

RETURN TO COMPARE THE SECOND OF THESE NOW ORDERED  
SETS WITH THE NEXT CONFIGURATION NOT PROCESSED



500 CONTINUE

00000670

IF NO CHANGES WERE MADE IN COMPARING EACH PAIR OF  
CONFIGURATION CODES, TERMINATE SORTING, OTHERWISE  
RETURN AND REPEAT THE COMPARISON CHECK

IF(CHANGE.LT.0.5) GOTO 510

CHANGE=0.0  
IROUND=IROUND-1  
GOTO 511

510 CONTINUE  
1106 CONTINUE

00000680  
00000690  
00000700  
00000710  
00000720  
00000730

READ FROM A DATA CARD THE FIRST COMPONENT CODE  
DESIRED AND THE POSITION IN WHICH IT MUST OCCUR  
FOR INCLUSION IN THE SUMMARY TABLE. IF THE CODE  
IS NEGATIVE TERMINATE

READ(5,1100) POSIT,DES  
IPOSIT=POSIT  
IDES=DES  
IF(IPOSIT.LE.0) GOTO 1101

00000740  
00000750  
00000760  
00000770

SEPARATE FROM THE CONFIGURATION CODE THE DIGIT  
IN THE DESIRED POSITION

KES=1  
DO 1102 KEY=1,IROUND  
IXPON=IPOSIT-4  
UPPER=CON(KEY)\*(10.0\*\*IXPON)  
ILOW=UPPER/10.0  
LOWER=ILOW  
LOWER=LOWER\*10.0  
IDIF=UPPER-LOWER

00000780  
00000790  
00000800  
00000810  
00000820  
00000830  
00000840  
00000850

IF THIS SEPARATED DIGIT IS EQUAL TO THAT REQUIRED,  
STORE THE ASSOCIATED SUMMARY DATA IN THE TABLE  
STORAGE MATRIX. IF IT IS NOT, RETURN AND CONSIDER THE  
NEXT CONFIGURATION CODE



```

1103 IF(1DIF.EQ.IDES) GOTO 1103
      GOTO 1102
      CONTINUE
      SUBLIS(KES)=CONC(KEY)
      CONDCD(KES)=CONDC(KEY)
      ZSUBD(KES)=SUBD(KEY)
      ZCMF(KES)=CMF(KEY)
      ZCVT(KES)=CVT(KEY)
      ZDIS(KES)=DIS(KEY)
      ZDFC(KES)=DFC(KEY)
      ZACDV(KES)=ACDV(KEY)
      ZAUGRT(KES)=AUGRT(KEY)
      ZBCCN(KES)=BCCN(KEY)
      KES=KES+1
1102 CONTINUE

```

```

0000860
0000870
0000880
0000890
0000900
0000910
0000920
0000930
0000940
0000950
0000960
0000970
0000980
0000990
0001000

```

PRINT THE TABLE HEADING AND IDENTIFY THE DIGIT  
AND POSITION REQUIRED FOR INCLUSION

```

WRITE(6,1104) IDES,IPOSIT
WRITE(6,269)
WRITE(6,300)

```

```

00001010
00001020
00001030

```

EXAMINE THE CONTENT OF EACH DATA LINE AND PRINT IT  
IN TABLE FORM WITH THE PROPER FORMAT

```

IF(KES.EQ.1) GOTO 1106
IDEDT=KES-1
DO 1105 KET=1,IDEDT
  BIGGER=DFC(KET)*10000.0
  ING=BIGGER
  SMALL=ING
  DFC(KET)=SMALL/10000.0
  IF(ZBCCN(KET).GT.0.5) GOTO 6100
  IF(CONDCD(KET).GT.0.5) GOTO 6093
  GOTO 6090
6100 IF(CONDCD(KET).GT.0.5) GOTO 6092
      GOTO 6091
6093 WRITE(6,301) SUBLIS(KET),ZCMF(KET),ZCVT(KET),
      CZDFC(KET),ZSUBD(KET),ZAUGRT(KET)
      GOTO 6086
6090 WRITE(6,302) SUBLIS(KET),ZCMF(KET),ZCVT(KET),
      CZDFC(KET),ZSUBD(KET),ZAUGRT(KET)

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00001190
00001200

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ZDIS(KET),
ZDIS(KET),

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GOTO 6661
6091 WRITE(6,303) SUBLIS(KET),ZCMF(KET),ZCVT(KET),
CZDFC(KET),ZSUBD(KET),ZAUGRT(KET)
GOTO 6661
6092 WRITE(6,304) SUBLIS(KET),ZCMF(KET),ZCVT(KET),
CZDFC(KET),ZSUBD(KET),ZAUGRT(KET)
6661 CONTINUE
1108 CONTINUE
1109 CONTINUE
GOTO 1106
1101 CONTINUE

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IF NO ADDITIONAL TABLES ARE REQUIRED, TERMINATE

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STOP
END

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ZDIS(KET),00001220
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ZDIS(KET),00001220
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The aircraft turbine engine has evolved to the point that current static test facility designs require modification to provide adequate service and growth potential. Current design procedures are inadequate in that they do not provide methods for the prediction of flow uniformity at the increased thrust and air flow rates now being required. Through the testing of a multiplicity of inlet models the effect of test cell inlet configuration on engine distortion level is evaluated. A method is developed for the correlation of inlet design characteristics with experimentally observed distortion levels. Together with the evaluation of augmentor performance in an associated thesis by Lt. David L. Bailey, this tentative correlation provides a basis for the development of a practical system for the prediction of the performance of proposed test cell designs.



14. KEY WORDS	LINK A		LINK B		LINK C	
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Jet engine test facilities						
Test cell design						
Environmental protection						
Duct flow						
Acoustic control techniques						
Jet mixing						
Industrial safety						
Automatic data acquisition						
Model tests						
Test facility construction						
Boundary layer growth						
Construction aerodynamics						

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